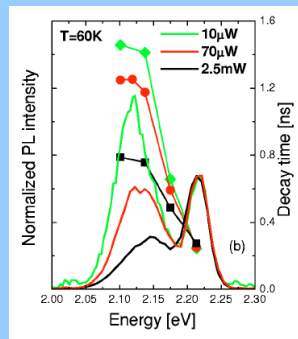




## Kropki kwantowe - część II własności optyczne

Sebastian Maćkowski

Instytut Fizyki  
Uniwersytet Mikołaja Kopernika

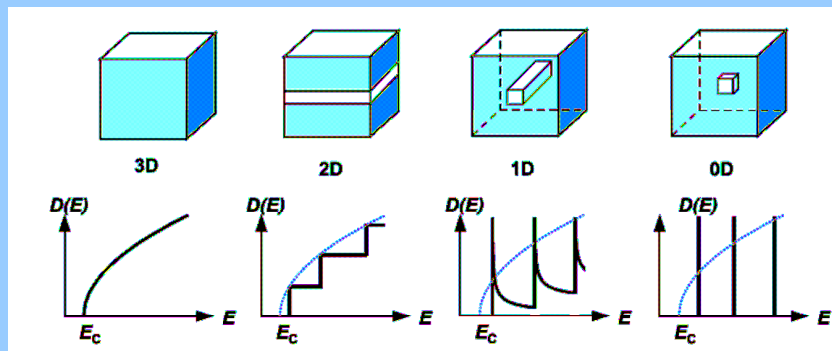


## Plan

1. Redystrybucja nośników między kropkami
2. Spektroskopia kwazi-rezonansowa
3. Oddziaływanie ekscytonu z fononem optycznym
4. Relaksacja spinowa ekscytonu w kropkach
5. Wygrzewanie kropek kwantowych

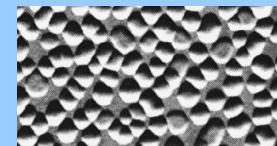


## Co to jest kropka kwantowa?

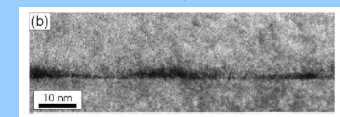


## Kropki samorosnące

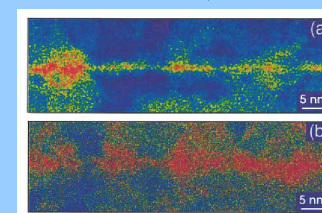
InAs/GaAs QDs



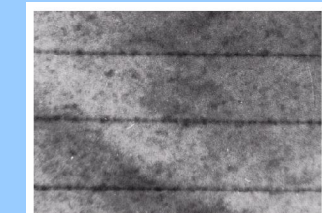
Si/Ge QDs



CdSe/ZnSe QDs

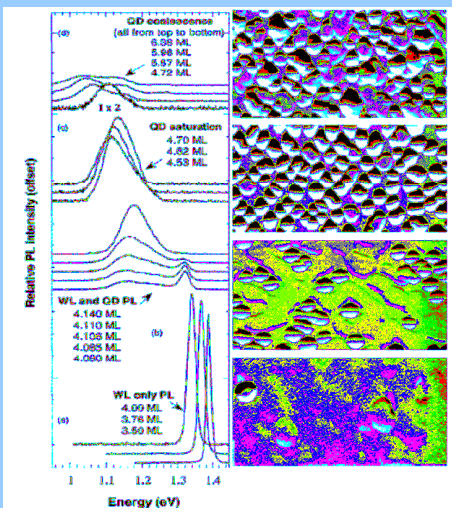


CdTe/ZnTe QDs





## Kropki III-V



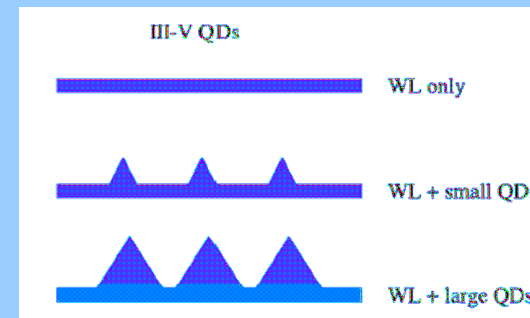
brak emisji z WL  
słaba intensywność emisji  
z kropek kwantowych

dwie linie:  
WL – stała energia, wąska linia  
QDs – zmienna energia, szeroka linia

energia przesuwa się ze  
wzrostem grubości warstwy  
InGaAs



## Kropki III-V



## Kropki III-V

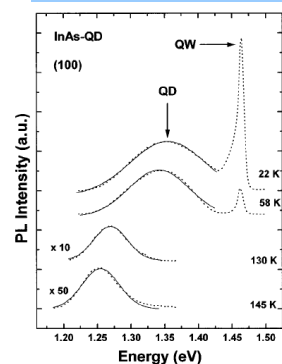
### Exciton localization and temperature stability in self-organized InAs quantum dots

D. I. Lubyshv, P.P. González-Borrero, E. Marega, Jr., E. Pettiprez, N. La Scala, Jr., and P. Basmaji  
Instituto de Física de São Carlos-Universidade de São Paulo, C.P. 369, CEP 13560-970 São Carlos, São Paulo, Brazil

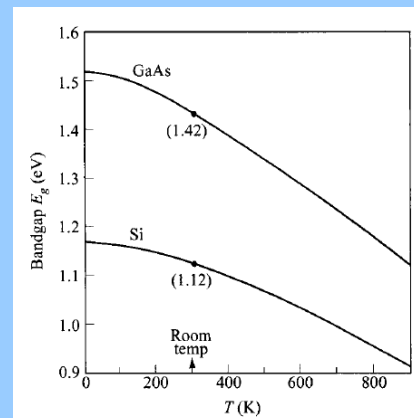
(Received 14 August 1995; accepted for publication 27 October 1995)

We investigated the temperature effect on exciton localization in self-organized InAs quantum dots. Quenching energy for excitons in reference quantum well and quantum dots was found to be 2 and 7 meV, respectively. Thermoactivation energy of electron-hole emission through a GaAs barrier in the quantum dots was measured as 46 meV. We observed an unusual decrease of photoluminescence peak fill width at half maximum with temperature, suggesting suppression of nonpredominant size quantum dot emissions due to carrier tunneling between nearby dots. © 1996 American Institute of Physics. [S0003-6951(96)01402-7]

warstwa zwilżająca jest kanałem  
umożliwiającym transport nośników  
między kropkami kwantowymi



## Zależność przerwy od T



	$E_g(0)$ (eV)	$\alpha$ (eV/K)	$\beta$ (K)
GaAs	1.519	$5.4 \times 10^{-4}$	204
Si	1.169	$4.9 \times 10^{-4}$	655

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}$$

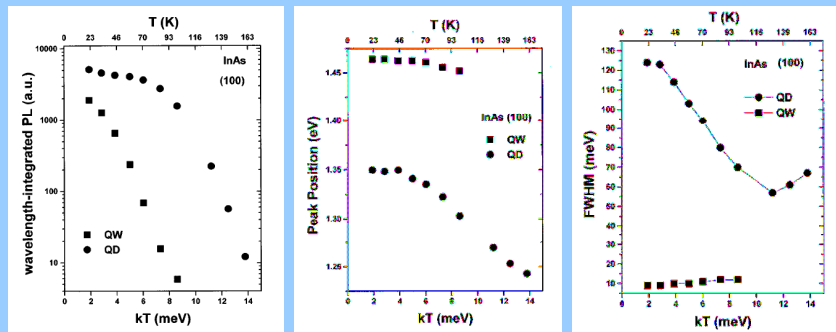
wzrost temperatury  
skutkuje zmniejszeniem  
przerwy energetycznej

ok. 30-50 meV/100K

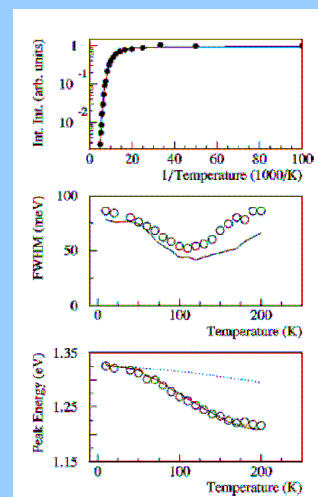
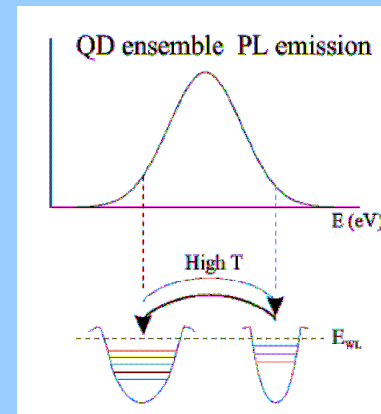


## Redystrybucja nośników

aktywowana termicznie redystrybucja nośników między kropkami kwantowymi o różnych energiach



## Redystrybucja nośników



## Kropki kwantowe II-VI

VOLUME 85, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JULY 2000

### Evidence for 2D Precursors and Interdiffusion in the Evolution of Self-Assembled CdSe Quantum Dots on ZnSe

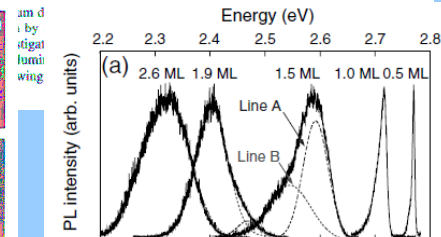
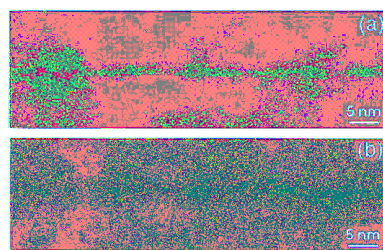
C. S. Kim,<sup>1</sup> M. Kim,<sup>1</sup> J. K. Furdyna,<sup>1</sup> M. Dobrowolska,<sup>1,\*</sup> S. Lee,<sup>2</sup> H. Rho,<sup>3</sup> L. M. Smith,<sup>3</sup> Howard E. Jackson,<sup>3</sup> E. M. James,<sup>4</sup> Y. Xin,<sup>4</sup> and N. D. Browning<sup>4</sup>

<sup>1</sup>Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556

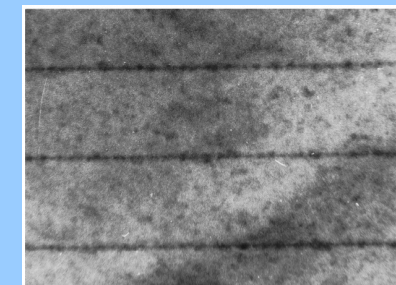
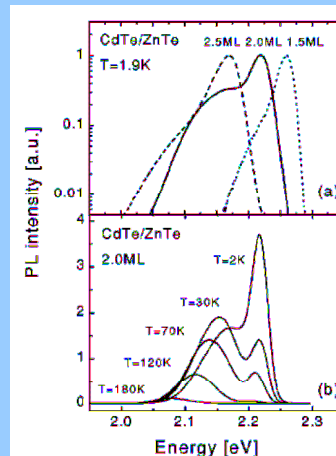
<sup>2</sup>Department of Electronic Materials Engineering, Kwangju University, Seoul, 139-701 Korea

<sup>3</sup>Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221

<sup>4</sup>Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607  
(Received 22 December 1999)



## Kropki kwantowe II-VI



dla kropek II-VI w miarę osadzania materiału przesuwają się energia emisji ze studni kwantowej



# Kropki kwantowe II-VI



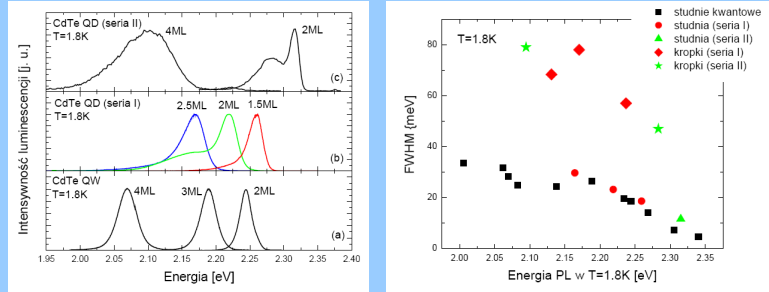
Thin Solid Films 412 (2002) 96-100



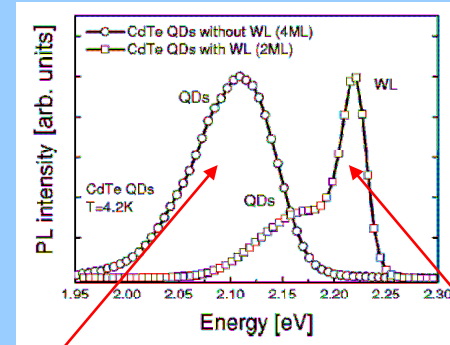
## CdTe/ZnTe quantum dots—growth and optical properties

Sebastian Mackowski\*

Institute of Physics Polish Academy of Sciences, Al. Lotników 32/46, Warsaw, Poland



# Dwa rodzaje kropek



kropki izolowane

kropki połączone warstwą zwilżającą



# Redystrybucja nośników

PHYSICAL REVIEW B 69, 205325 (2004)

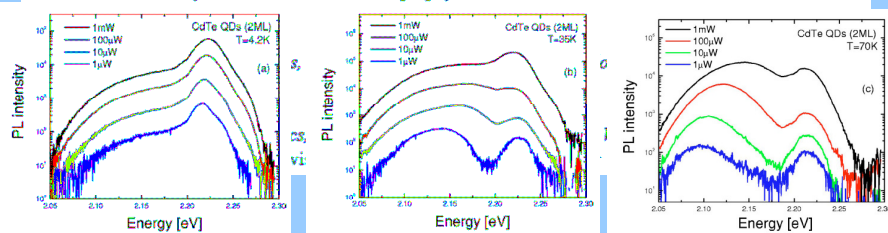
## Impact of carrier redistribution on the photoluminescence of CdTe self-assembled quantum dot ensembles

S. Mackowski\*

Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221-0011, USA

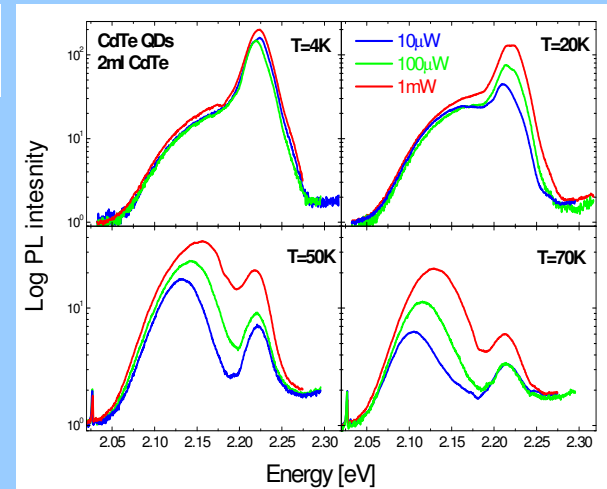
G. Prechtl and W. Heiss

Institut für Halbleiter- und Festkörperphysik, Universität Linz, 4040 Linz, Austria



# Widma znormalizowane

uniform 2D WL + QDs (CdTe QDs)



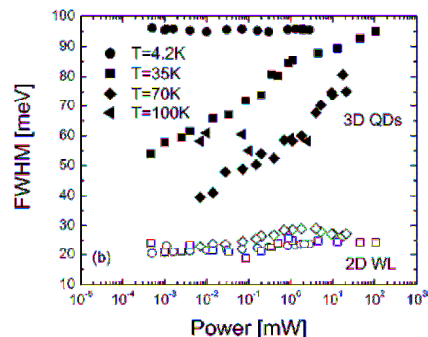
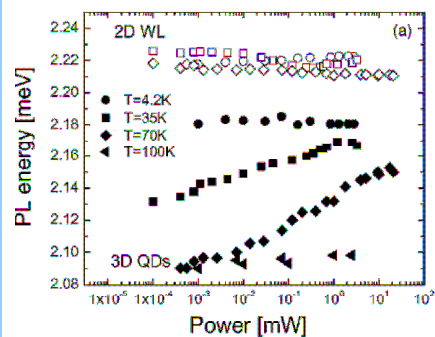


## Redystrybucja nośników

uniform 2D WL + QDs (CdTe QDs)



trzy obszary:  $T=4.2\text{K}$   
 $30\text{K} < T < 70\text{K}$   
 $T=100\text{K}$

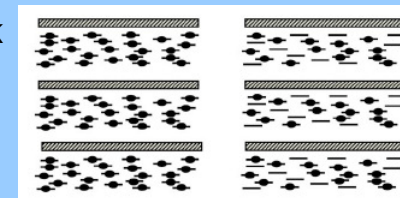


## Redystrybucja nośników

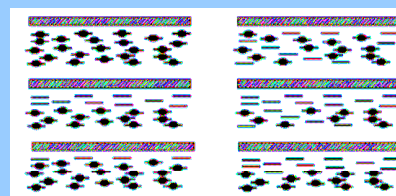
uniform 2D WL + QDs (CdTe QDs)



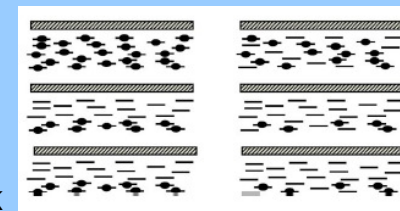
$T=4.2\text{K}$



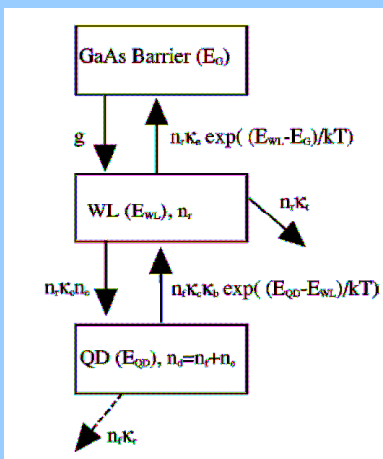
$30\text{K} < T < 70\text{K}$



$T=100\text{K}$



## Model teoretyczny



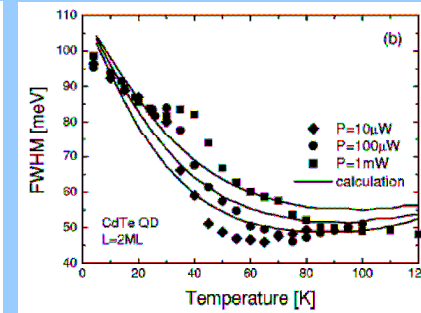
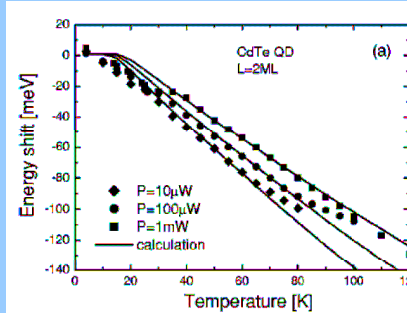
założenia modelu

- (a) The capture of photoexcited carriers from the ZnTe barrier into the QD's takes place only via the 2D WL. Analogously, we neglect a direct carrier escape out of QD's to the ZnTe barrier.
- (b) The carriers in the WL could either be captured by QD's or they recombine radiatively or nonradiatively in the WL.
- (c) Each QD can be populated by only one electron-hole pair, and the initial QD population is determined by the statistical distribution of QD ground-state energies within the ensemble. The energy distribution of QD's is identical to the PL spectrum measured at  $T=4.2\text{K}$ .
- (d) The radiative recombination time of excitons is the same for all QD's, and it does not depend on either size or shape (i.e., the emission energy) of QD's.
- (e) The probability of thermal escape from QD to WL ( $\gamma$ ) is proportional to  $\exp(-\Delta E/k_B T)$ , where  $\Delta E$  is the difference between the energy of the QD and the energy of the WL.



## Model teoretyczny

uniform 2D WL + QDs (CdTe QDs)





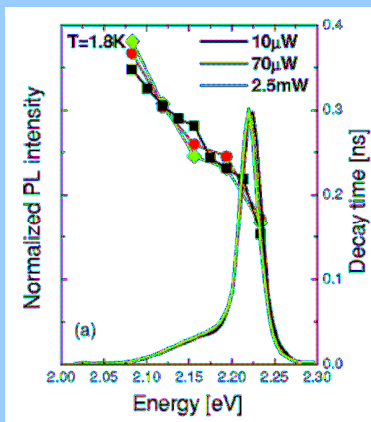
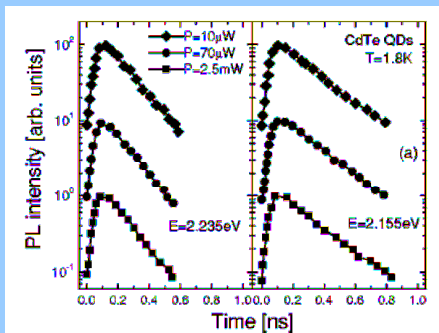


## Dynamika ekscytonów

uniform 2D WL + QDs (CdTe QDs)



T=1.8K

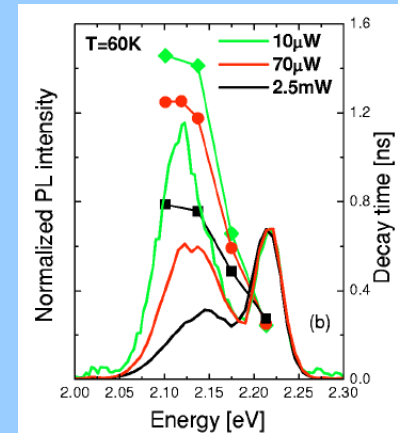
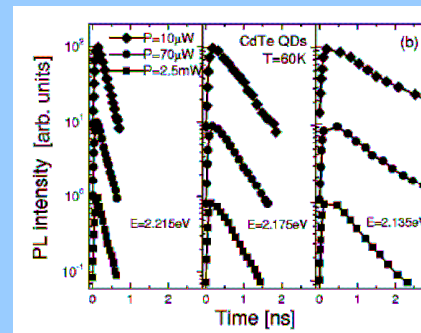


## Dynamika ekscytonów

uniform 2D WL + QDs (CdTe QDs)



T=60K

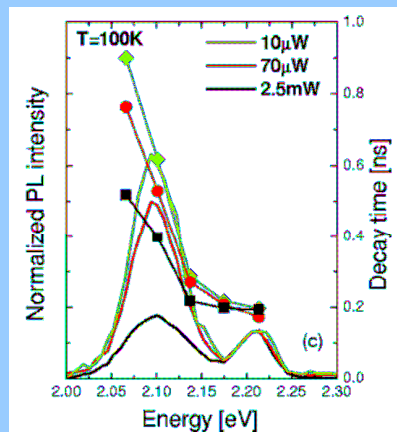
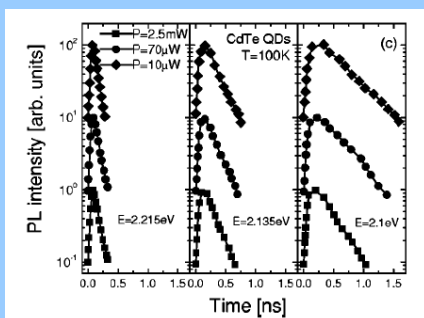


## Dynamika ekscytonów

uniform 2D WL + QDs (CdTe QDs)

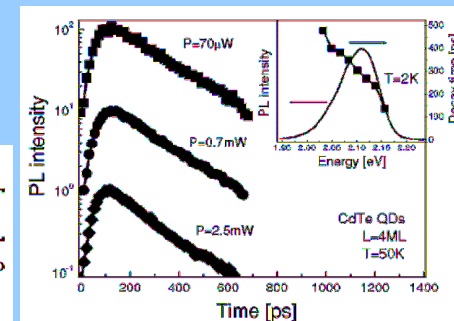
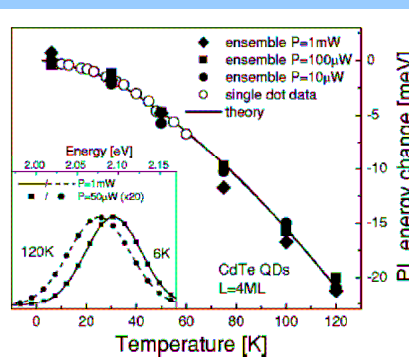


T=100K



## Kropki izolowane

fully developed QDs



dla izolowanych kropek kwantowych nie występują efekty redystrybucji nośników



# Spektroskopia ansamblu

PHYSICAL REVIEW B

VOLUME 56, NUMBER 16

15 OCTOBER 1997-II

## Energy relaxation by multiphonon processes in InAs/GaAs quantum dots

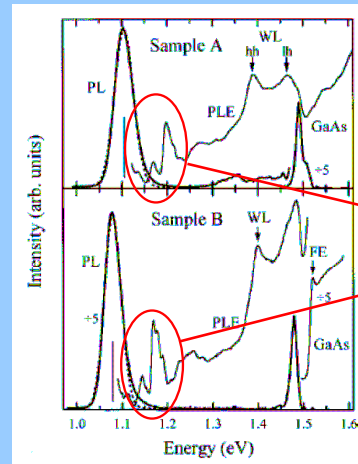
R. Heitz, M. Veit, N. N. Ledentsov, A. Hoffmann, and D. Bimberg  
*Institut für Festkörperphysik, Technische Universität Berlin, 10623 Berlin, Germany*

V. M. Ustinov, P. S. Kop'ev, and Zh. I. Alferov  
*A. F. Ioffe Physical-Technical Institute, 194021, St. Petersburg, Russia*  
(Received 10 January 1997)

Carrier relaxation and recombination in self-organized InAs/GaAs quantum dots (QD's) is investigated by photoluminescence (PL), PL excitation (PLE), and time-resolved PL spectroscopy. We demonstrate involving phonon scattering to be the dominant intradot carrier-relaxation mechanism. Multiphonon processes involving up to four LO phonons from either the InAs QD's, the InAs wetting layer, or the GaAs barrier are resolved. The observation of multiphonon resonances in the PLE spectra of the QD's is discussed in analogy to hot exciton relaxation in higher-dimensional semiconductor systems and proposed to be intricately bound to the inhomogeneity of the QD ensemble in conjunction with a competing nonradiative recombination channel observed for the excited hole states. Carrier capture is found to be a cascade process with the initial capture into excited states taking less than a few picoseconds and the multiphonon (involving three LO phonons) relaxation time of the first excited hole state being 40 ps. The [001] hole state presents a relaxation bottleneck that determines the ground-state population time after nonresonant excitation. For the small self-organized InAs/GaAs QD's the intradot carrier relaxation is shown to be faster than radiative ( $>1$  ns) and nonradiative ( $\sim 100$  ps) recombination explaining the absence of a "phonon bottleneck" effect in the PL spectra. [S0163-1829(97)09340-5]



# Wzbudzenia kropek

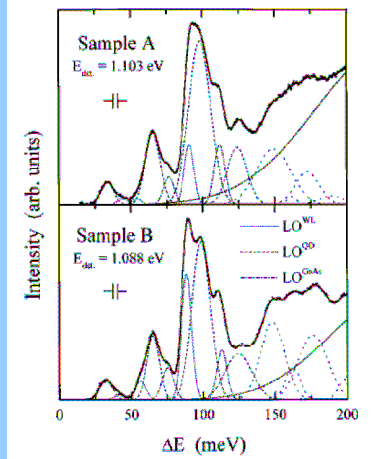
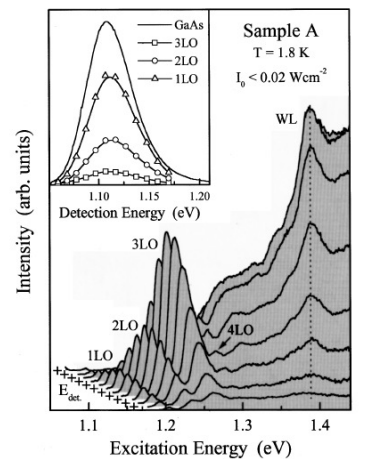


obecność matrycy GaAs, warstwy zwilżającej InAs **OK**

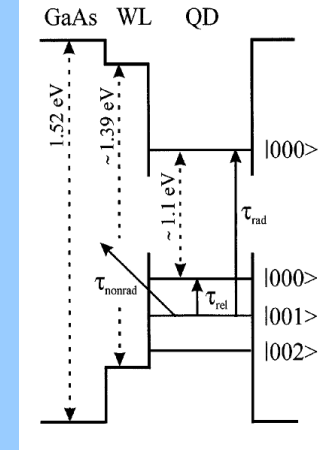
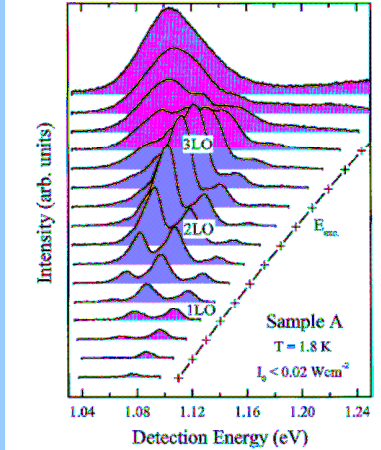
co to jest ???



# Widmo wzbudzenia



# Widmo emisji





## Oddziaływanie z fononem

PHYSICAL REVIEW B 70, 125306 (2004)

### Resonant spectroscopy of II-VI self-assembled quantum dots: Excited states and exciton-longitudinal optical phonon coupling

T. A. Nguyen, S. Mackowski,\* H. E. Jackson, and L. M. Smith  
Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221-0011, USA

J. Wrobel, K. Fronc, G. Karczewski, and J. Kossut  
Institute of Physics, Polish Academy of Science, Warsaw, Poland

M. Dobrowolska and J. K. Furdyna  
Department of Physics, University of Notre Dame, Indiana, USA

W. Heiss

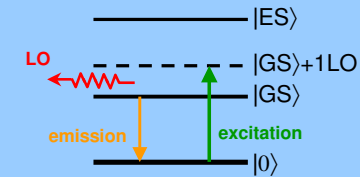
Institut für Halbleiter- und Festkörperphysik, Johannes Kepler Universität Linz, Austria

(Received 4 September 2003; revised manuscript received 16 April 2004; published 13 September 2004)



## Spektroskopia rezonansowa

absorpcja z wykorzystaniem fononów optycznych



kontrola polaryzacji światła pobudzającego daje możliwość pomiaru dynamiki spinowej ekscytynu

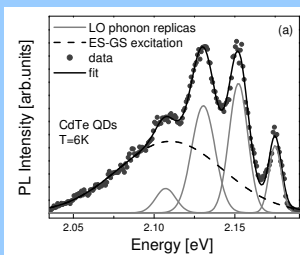
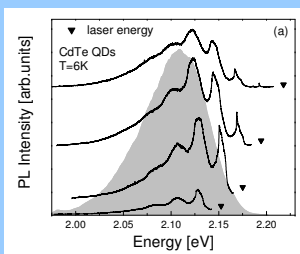
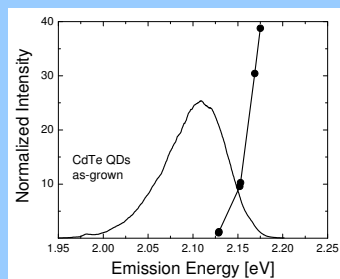


## Kropki izolowane



fully developed QDs

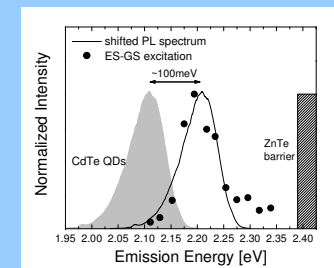
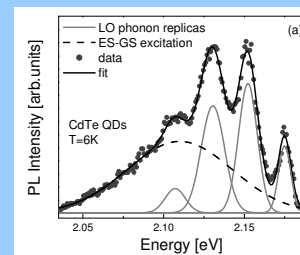
oddziaływanie ekscytynu z fononem optycznym



## Stany wzbudzone



fully developed QDs



stany wzbudzone mają podobny rozkład do rozkładu stanów podstawowych, są przesunięte o około 100 meV w stronę wyższych energii

o naturze stanów wzbudzonych – za dwa tygodnie ?





# Spin ekscytonu

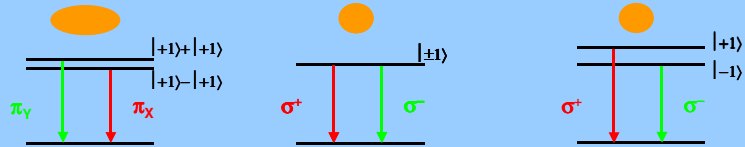
**B=0T**

**B>0T**

asymmetric QD

symmetric QD

symmetric QD



o poziomach energetycznych dokładniej – za dwa tygodnie ?



# Spin ekscytonu

VOLUME 86, NUMBER 8

PHYSICAL REVIEW LETTERS

19 FEBRUARY 2001

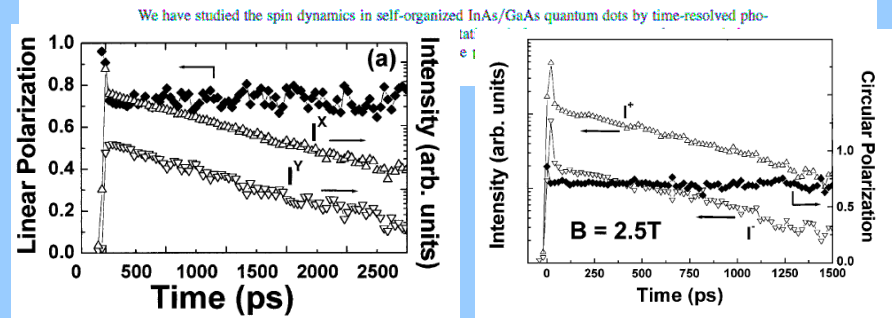
## Spin Relaxation Quenching in Semiconductor Quantum Dots

M. Paillard,<sup>1</sup> X. Marie,<sup>1</sup> P. Renucci,<sup>1</sup> T. Amand,<sup>1</sup> A. Jbeli,<sup>1</sup> and J. M. Gérard<sup>2</sup>

<sup>1</sup>Laboratoire de Physique de la Matière Condensée, INSA-CNRS, 135 Avenue de Rangueil, 31077 Toulouse cedex, France

<sup>2</sup>France Télécom R&D, 196 Avenue H. Ravera 92220 Bagneux, France

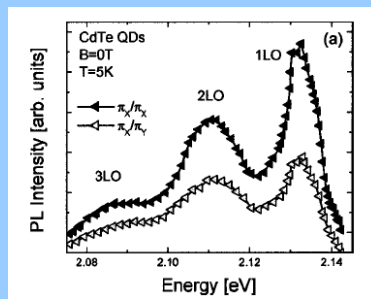
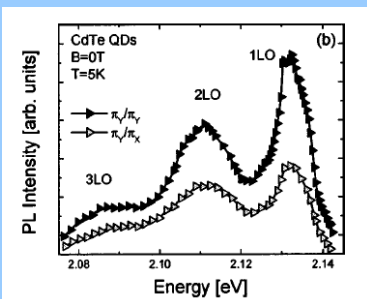
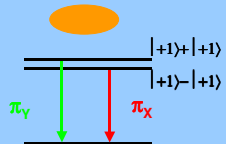
(Received 28 June 2000)



# Spin ekscytonu

asymmetric QD

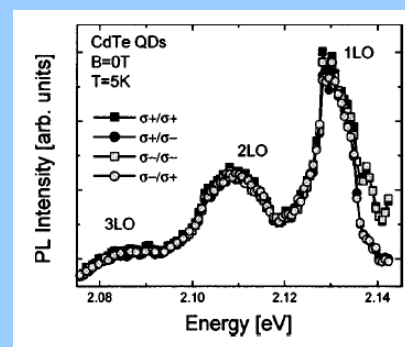
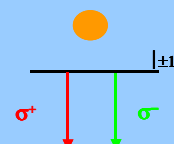
czas relaksacji spinu >> czas rekombinacji



# Spin ekscytonu

symmetric QD

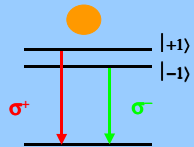
czas relaksacji spinu << czas rekombinacji



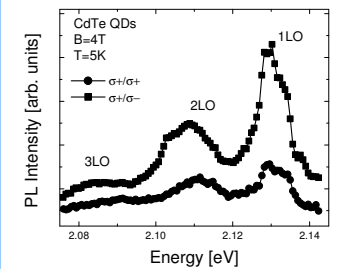
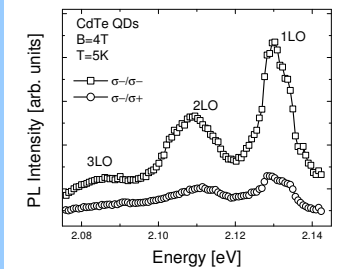


## Spin ekscytonu

symmetric QD



czas relaksacji spinu >> czas rekombinacji



## Spin ekscytonu

APPLIED PHYSICS LETTERS

VOLUME 83, NUMBER 26

29 DECEMBER 2003

### Exciton spin relaxation time in quantum dots measured by continuous-wave photoluminescence spectroscopy

S. Mackowski,<sup>a)</sup> T. A. Nguyen, H. E. Jackson, and L. M. Smith  
*Department of Physics, University of Cincinnati, Cincinnati, Ohio 45321-0011*

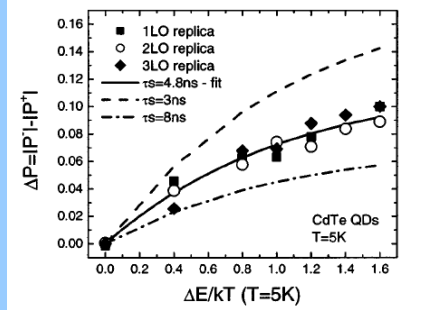
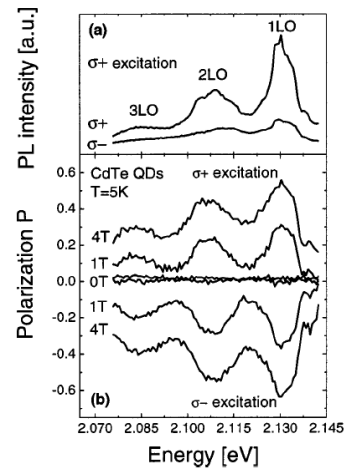
J. Kossut and G. Karczewski  
*Institute of Physics, Polish Academy of Sciences, Warszawa, Poland*

(Received 4 August 2003; accepted 3 November 2003)

We demonstrate a method of measuring the exciton spin relaxation time in semiconductor nanostructures by continuous-wave photoluminescence. We find that for self-assembled CdTe quantum dots (QDs) the degree of circular polarization of emission is larger when exciting polarized excitons into the lower energy spin state ( $\sigma^-$ -polarized) than in the case when the excitons are excited into the higher energy spin state ( $\sigma^+$ -polarized). A simple rate equation model gives the exciton spin relaxation time in CdTe QDs equal to  $\tau_R = 4.8 \pm 0.3$  ns, significantly longer than the QD exciton recombination time  $\tau_R = 300$  ps. © 2003 American Institute of Physics. [DOI: 10.1063/1.1636516]



## Spin ekscytonu



$$\Delta P = |P^-| - |P^+| = \frac{n_{-}^- - n_{+}^- - n_{+}^+ - n_{-}^+}{n_{-}^- + n_{+}^- + n_{+}^+ + n_{-}^+}$$

$$= \frac{2\tau_R(e^{\Delta E/KT} - 1)}{\tau_R + e^{\Delta E/KT}(\tau_R + \tau_S)}$$

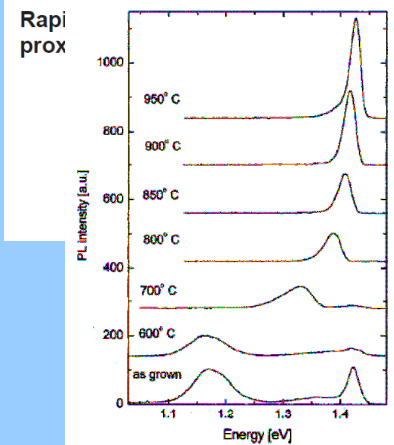


## Wyrzewanie kropek

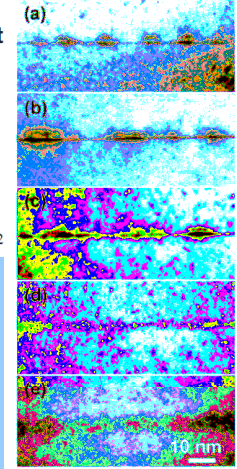
APPLIED PHYSICS LETTERS

VOLUME 79, NUMBER 1

OCTOBER 2001

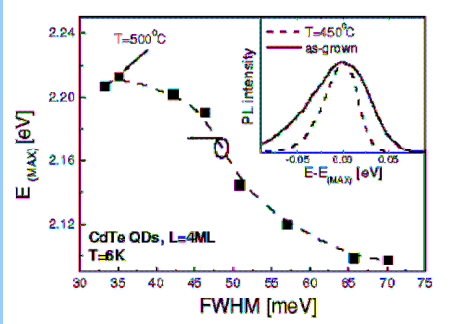
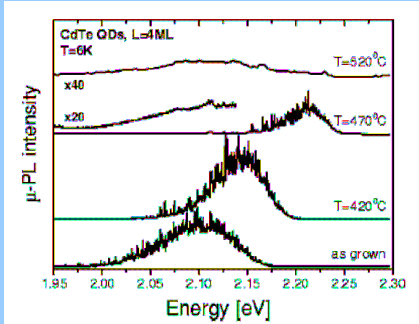


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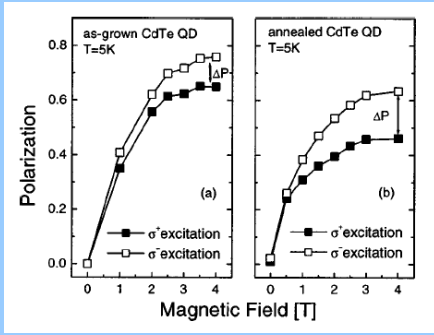
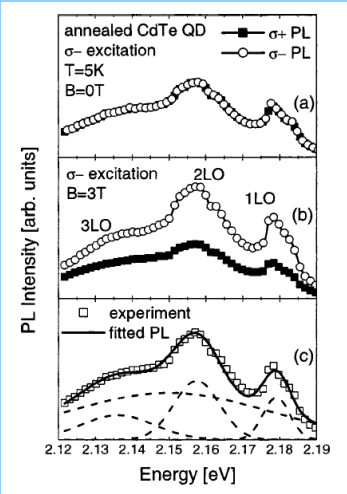
# Wyrzwanie kropek CdTe



wyrzwanie prowadzi do przesunięcia energii emisji, zawężenia linii, skrócenia czasu rekombinacji



# Spin ekscytonu



dla kropek wygrzewanych różnica między stopniami polaryzacji jest większa niż dla kropek przed wygrzaniem



# Porównanie

