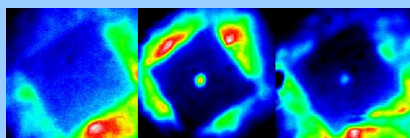




## Kropki kwantowe - część III spektroskopia pojedynczych kropek kwantowych

Sebastian Maćkowski  
Instytut Fizyki  
Uniwersytet Mikołaja Kopernika



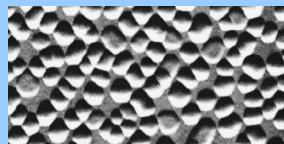
## Plan

1. Techniki pomiarowe
2. Podstawowe wyniki
3. Struktura ekscytynu w kropce
4. Relaksacja spinowa ekscytynu w kropkach
5. Natura stanów wzbudzonych

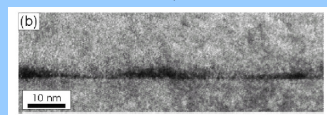


## Kropki samorosnące

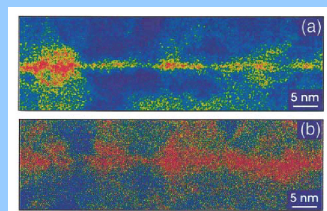
InAs/GaAs QDs



Si/Ge QDs



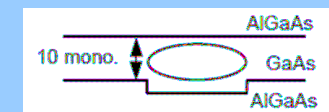
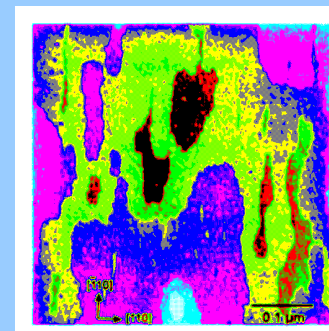
CdSe/ZnSe QDs



CdTe/ZnTe QDs

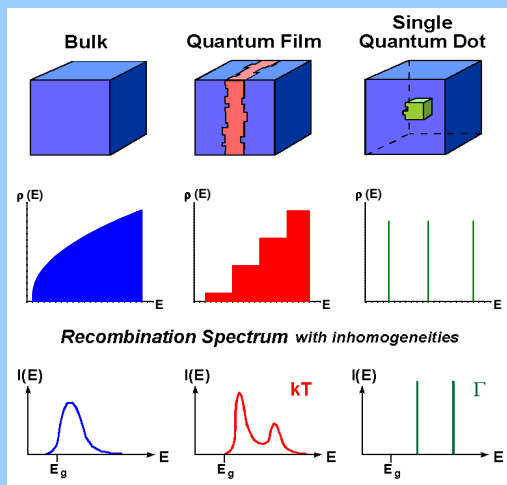


## Kropki – fluktuacje szerokości



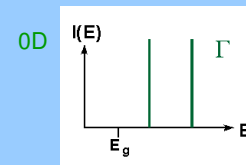


## Gęstość stanów



## Różnorodność kropek

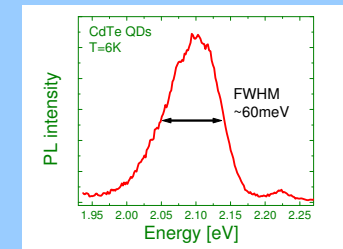
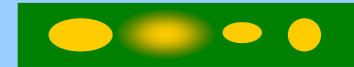
recombination spectrum of a single quantum dot



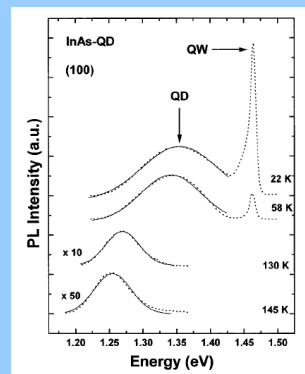
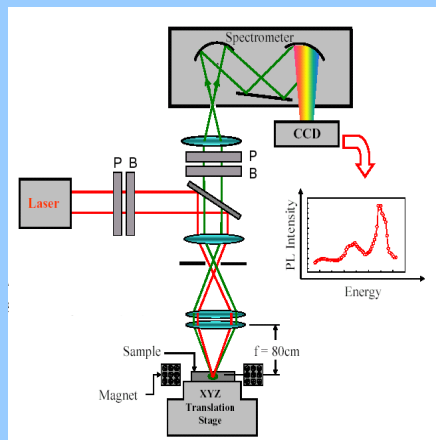
$\delta$ -like density of states

the ensemble QD emission shows strong inhomogeneous broadening

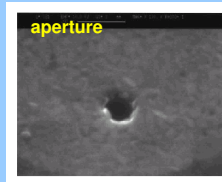
quantum dots in the ensemble are not identical



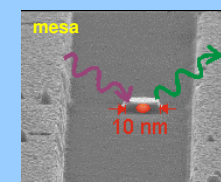
## Techniki eksperymentalne



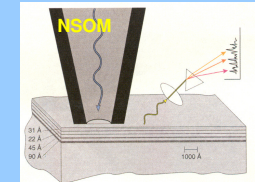
## Techniki eksperymentalne



D. Park, et al.,  
JVST B 16 (1998) 3891



<http://www.physik.uni-wuerzburg.de/TEP/index.html>



H. F. Hess, et al.,  
Science 264 (1996) 1740

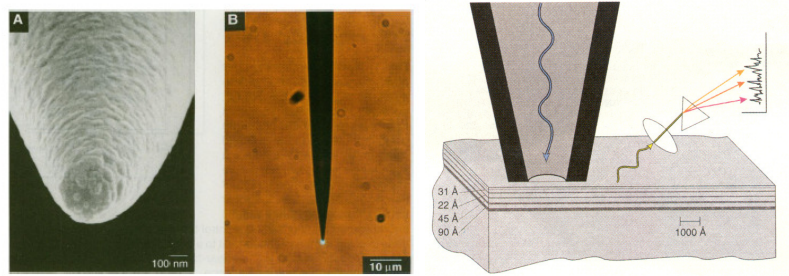
- ) low throughput
- ) no mapping possible
- ) fabrication
- ) no statistical information about QD properties



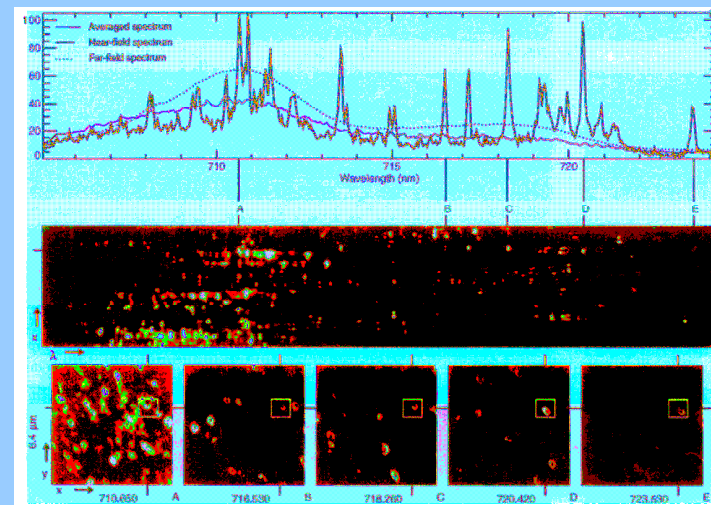
## Mikroskopia bliskiego pola

### Near-Field Optics: Microscopy, Spectroscopy, and Surface Modification Beyond the Diffraction Limit

Eric Betzig and Jay K. Trautman



## Mikroskopia bliskiego pola



## Mikroskopia bliskiego pola

PHYSICAL REVIEW B

VOLUME 54, NUMBER 24

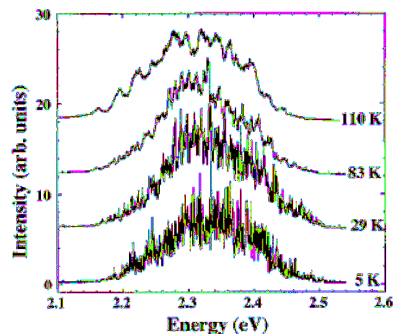
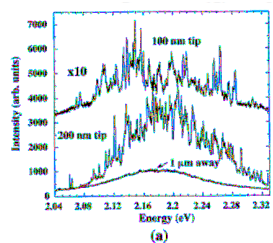
15 DECEMBER 1996-II

### Near-field optical spectroscopy of localized excitons in strained CdSe quantum dots

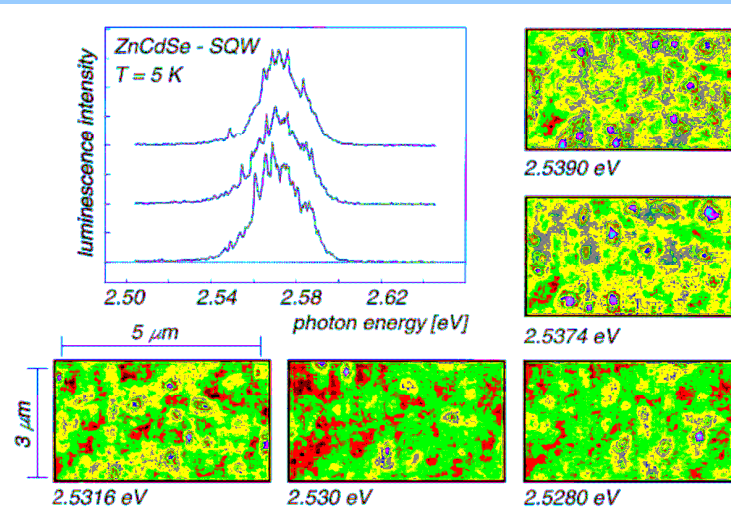
F. Flack and N. Samarth

Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802

V. Nikitin, P. A. Crowell, J. Shi, J. Levv, and D. D. Awschalom

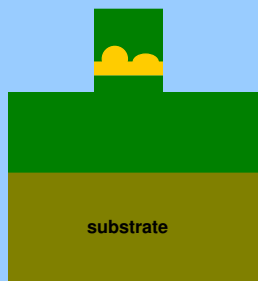
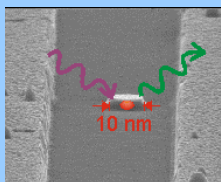


## Katodoluminescencja





# Wytrawianie mez



# Pierwsze wyniki

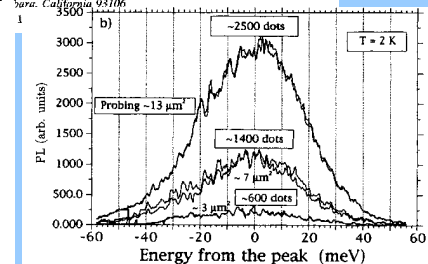
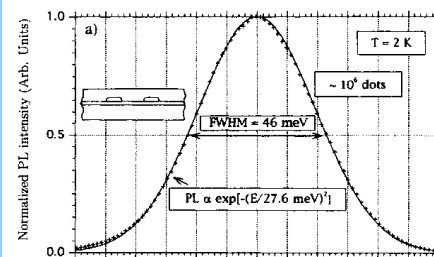
PHYSICAL REVIEW B VOLUME 50, NUMBER 11 15 SEPTEMBER 1994-1

## Visible photoluminescence from $N$ -dot ensembles and the linewidth of ultrasmall $\text{Al}_y\text{In}_{1-y}\text{As}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ quantum dots

S. Fafard and R. Leon  
Center for Quantized Electronic Structures (QUEST), University of California, Santa Barbara, California 93106

D. Leonard  
Center for Quantized Electronic Structures (QUEST) and Materials Department, University of California, Santa Barbara, California 93106

J. L. Merz and P. M. Petroff  
Center for Quantized Electronic Structures (QUEST) and Electrical and Computer Engineering Department, Santa Barbara, California 93106



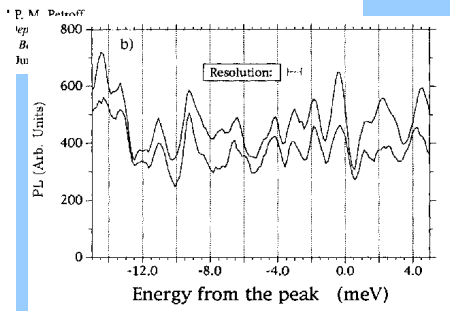
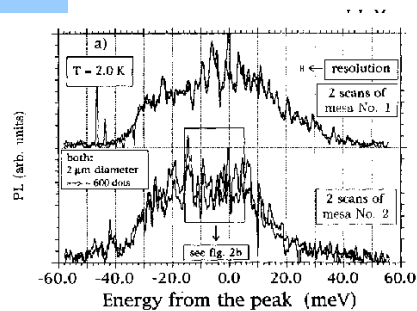
# Pierwsze wyniki

PHYSICAL REVIEW B VOLUME 50, NUMBER 11 15 SEPTEMBER 1994-1

## Visible photoluminescence from $N$ -dot ensembles and the linewidth of ultrasmall $\text{Al}_y\text{In}_{1-y}\text{As}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ quantum dots

S. Fafard and R. Leon  
Center for Quantized Electronic Structures (QUEST), University of California, Santa Barbara, California 93106

D. Leonard  
Center for Quantized Electronic Structures (QUEST) and Materials Department, University of California, Santa Barbara, California 93106

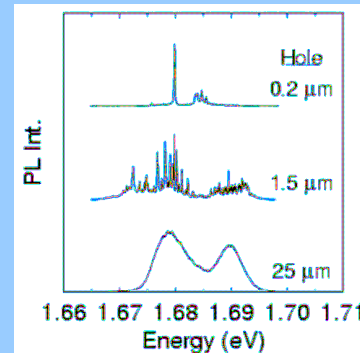
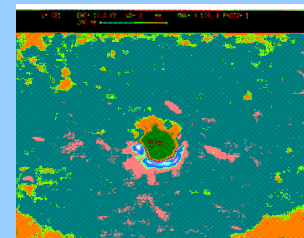


# Apertury

## Excited state spectroscopy of excitons in single quantum dots

D. Gammon,<sup>a)</sup> E. S. Snow, and D. S. Katzer  
Naval Research Laboratory, Washington, DC 20375-5347

(Received 10 March 1995; accepted for publication 8 August 1995)







## Apertury

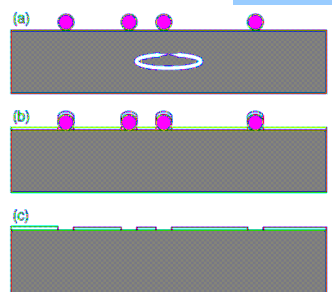
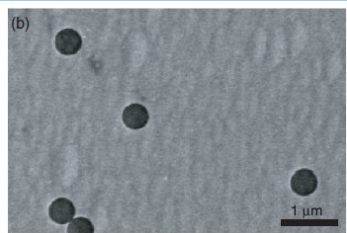
INSTITUTE OF PHYSICS PUBLISHING  
Nanotechnology 14 (2003) 675-679

NANOTECHNOLOGY  
PII: S0957-4484(03)56738-1

### Nano-aperture fabrication for single quantum dot spectroscopy

Ulf Håkanson<sup>1</sup>, Jonas Persson, Filip Persson, Hans Svensson, Lars Montelius and Mikael K-J Johansson

Solid State Physics/Nanometer Consortium, Lund University, PO Box 118, SE-221 00 Lund, Sweden



## Najważniejsze wyniki

PHYSICAL REVIEW B

VOLUME 58, NUMBER 12

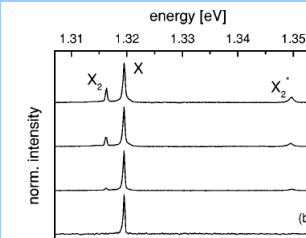
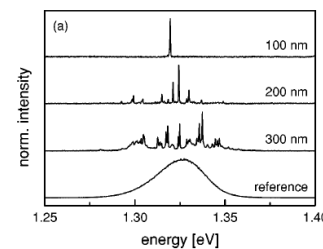
15 SEPTEMBER 1998-II

### Zeeman splitting of excitons and biexcitons in single $\text{In}_{0.60}\text{Ga}_{0.40}\text{As}/\text{GaAs}$ self-assembled quantum dots

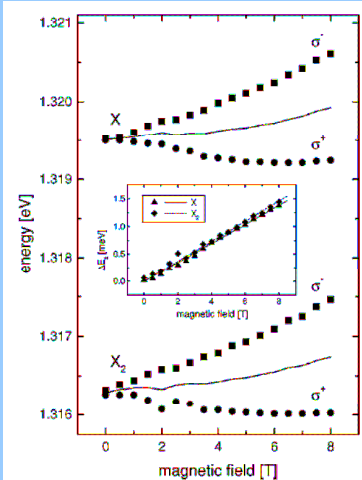
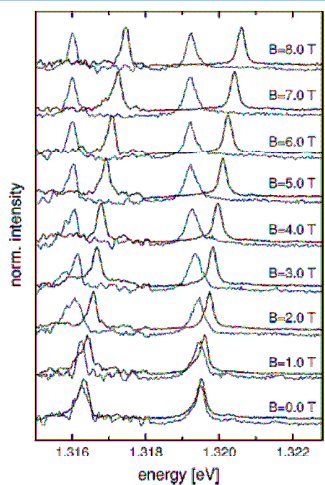
A. Kuther, M. Bayer, and A. Forchel  
*Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

A. Gorbunov and V. B. Timofeev  
*Institute of Solid State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Russia*

F. Schäfer and J. P. Reithmaier  
*Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*  
(Received 29 May 1998)



## Ekscyton w polu B



## Oddziaływanie wymiany

VOLUME 82, NUMBER 8

PHYSICAL REVIEW LETTERS

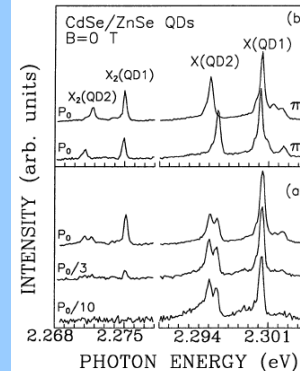
22 FEBRUARY 1999

### Fine Structure of Biexciton Emission in Symmetric and Asymmetric CdSe/ZnSe Single Quantum Dots

Ł. Zacher, R. Weigand, T. Köttermann, and A. Forchel  
*Technische Physik, Universität Würzburg, 97074 Würzburg, Germany*

E. Borovitskaya  
*Institute of Physics, RAS, 142432 Chernogolovka, Russia*

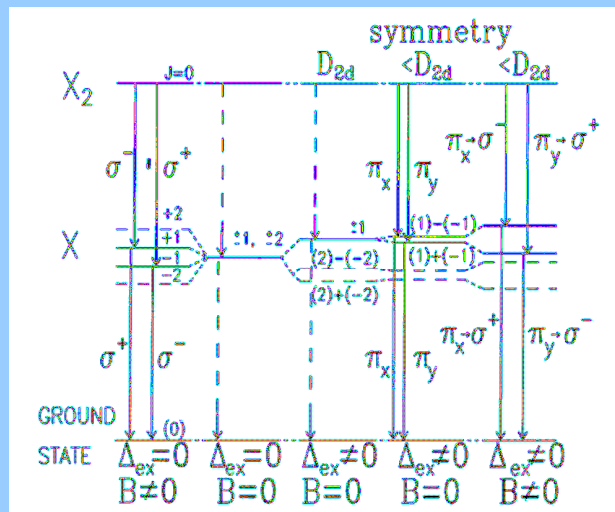
M. Leonardi and D. Hommel  
*Physik, Universität Bremen, 28359 Bremen, Germany*  
Received 12 October 1998



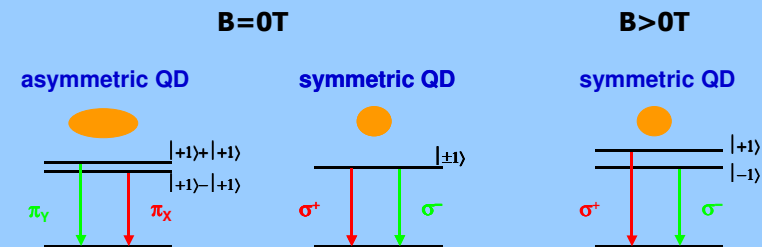
rozszczerzenie wymiany dla ekscytonu w asymetrycznej kropce



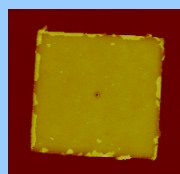
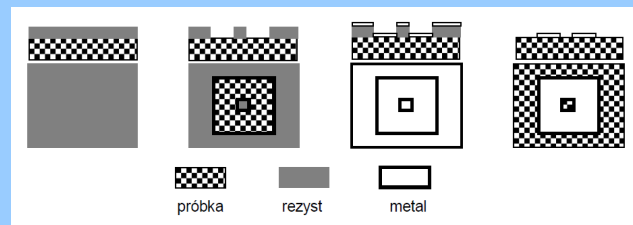
## Struktura ekscytonu w kropce



## Struktura ekscytonu w kropce



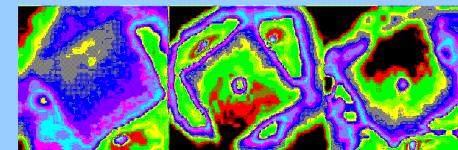
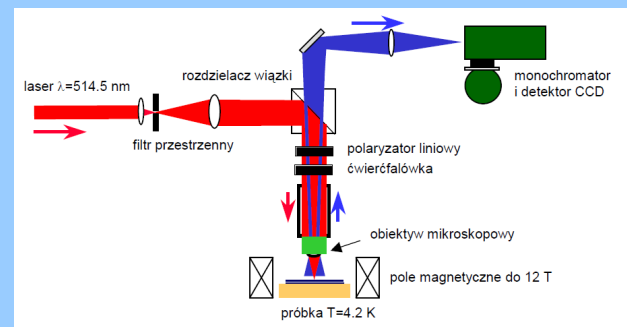
## Mikroluminescencja



150 nm

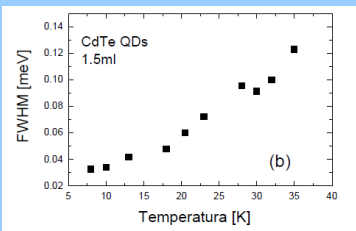
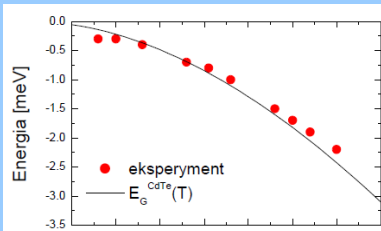
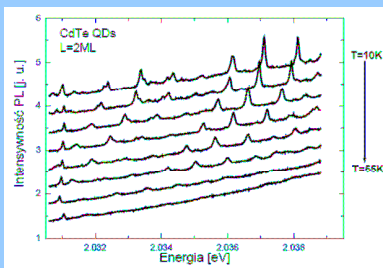
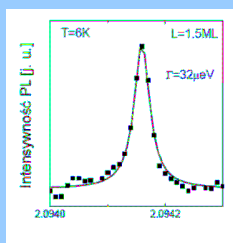


## Układ pomiarowy

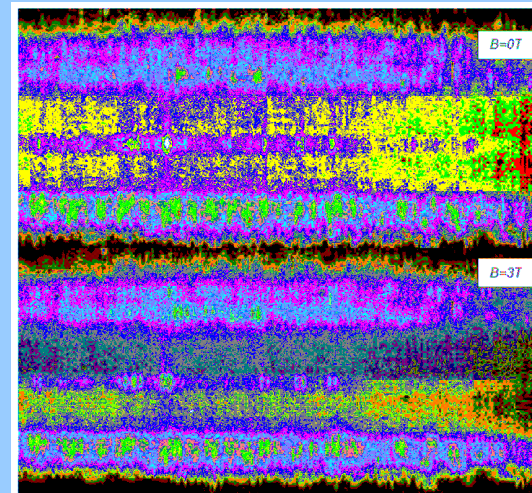
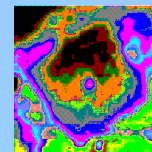
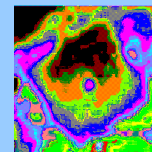




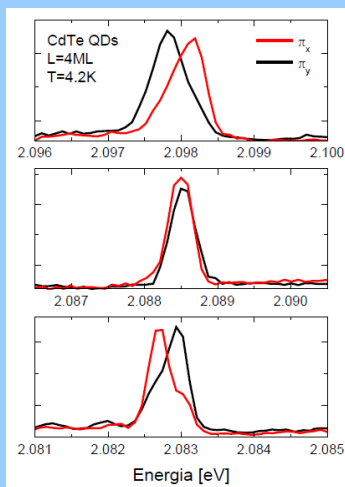
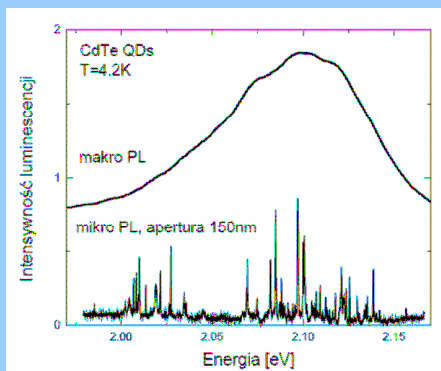
## Szerokość linii



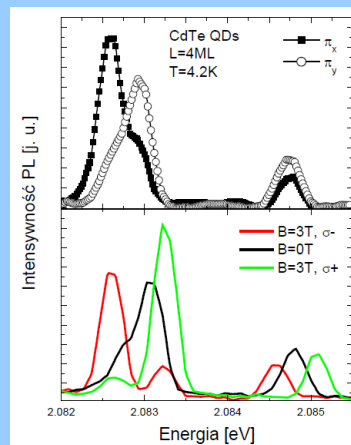
## Spektroskopia



## Spektroskopia



## Ekscyton w kropce kwantowej



rozszczerzenie spinowe

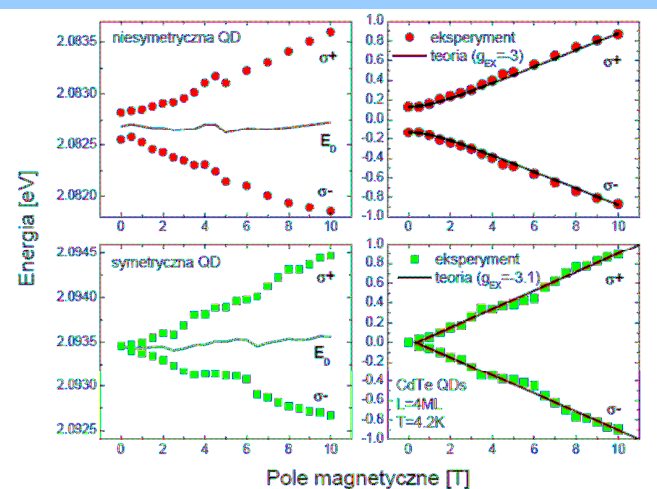
$$E_{1,2} = \frac{1}{2} (\delta_0 \pm \sqrt{(g_1 \mu_B B)^2 + \delta_1^2})$$

przesunięcie diamagnetyczne

$$E_D = \frac{e^2}{8} \left( \frac{\langle r_e \rangle}{m_e} + \frac{\langle r_h \rangle}{m_h} \right) B^2$$

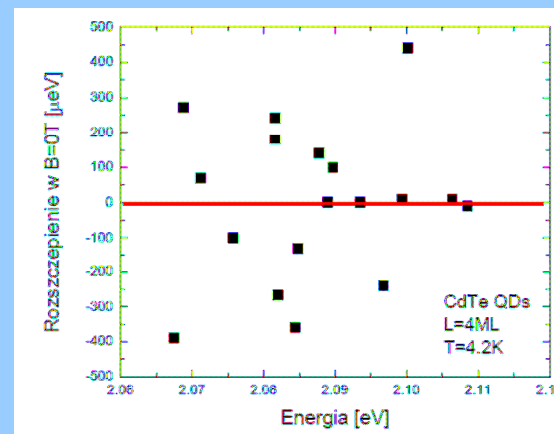


## Ekscyton w kropce kwantowej



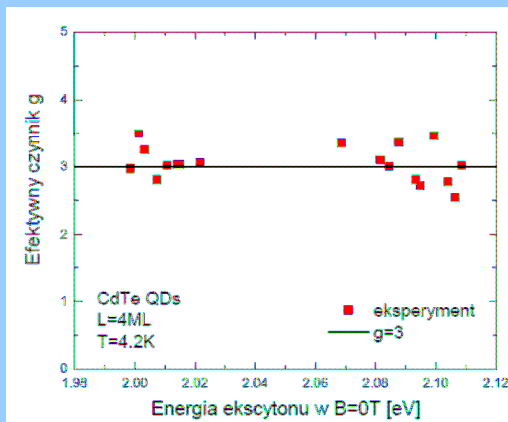
## Statystyka

rozszczenie wymiany



## Statystyka

czynnik g ekscytonu

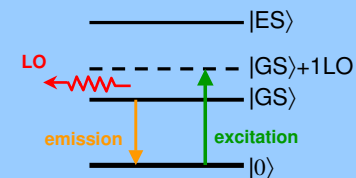


dla B=4T  
rozszczenie ~ 1meV



## Spektroskopia rezonansowa

absorpcja z wykorzystaniem fononów optycznych

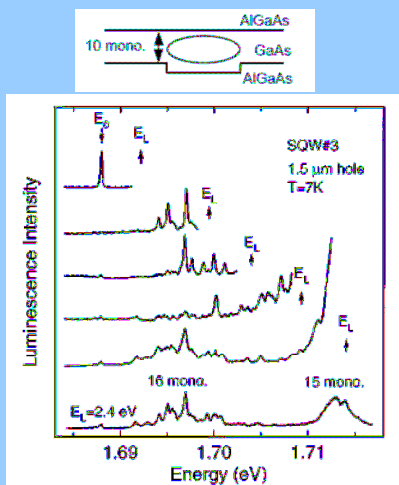
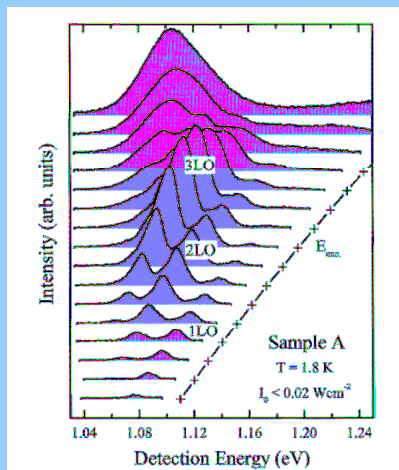


kontrola polaryzacji światła pobudzającego daje  
możliwość pomiaru dynamiki spinowej ekscytonu

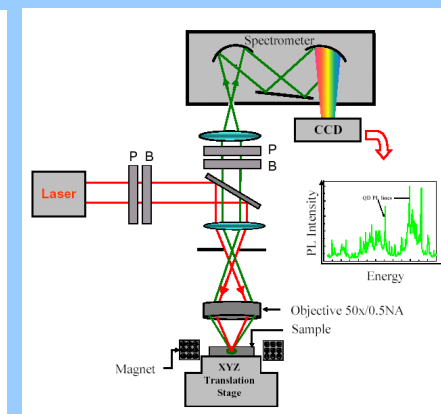
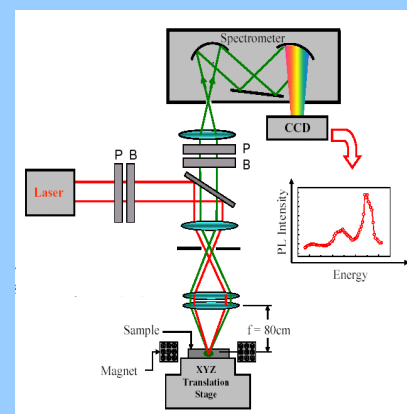




## Widmo emisji

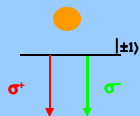


## Mikroluminescencja

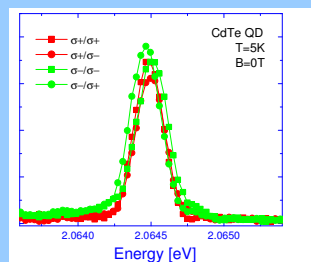
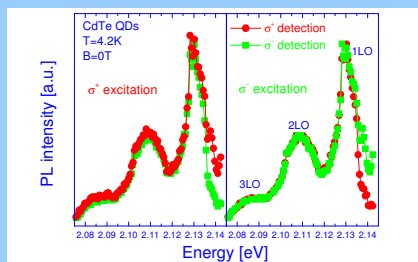


## Spin ekscytonu

symmetric QD



czas relaksacji spinu  $\ll$  czas rekombinacji

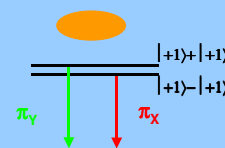


S. Mackowski *et al.*, PRB 70 (2004) 245312

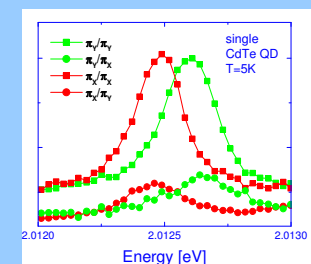
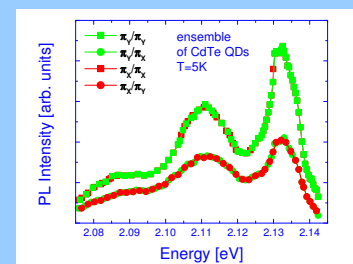


## Spin ekscytonu

asymmetric QD



czas relaksacji spinu  $\gg$  czas rekombinacji

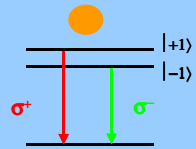


S. Mackowski *et al.*, PRB 70 (2004) 245312

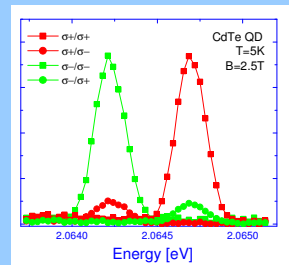
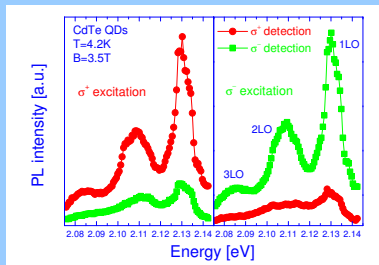


## Spin ekscytonu

symmetric QD



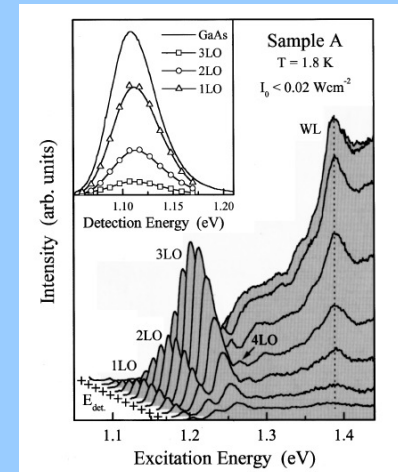
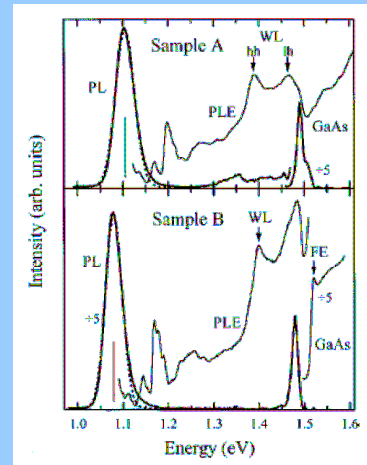
czas relaksacji spinu >> czas rekombinacji



S. Mackowski *et al.*, PRB 70 (2004) 245312

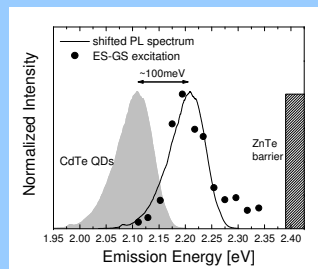
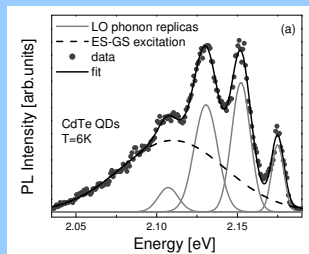


## Widmo wzbudzenia kropek



## Stany wzbudzone

fully developed QDs



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



## Widmo wzbudzenia

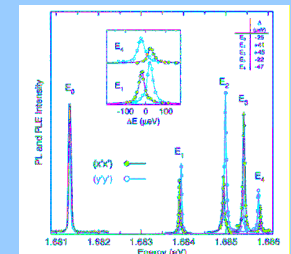
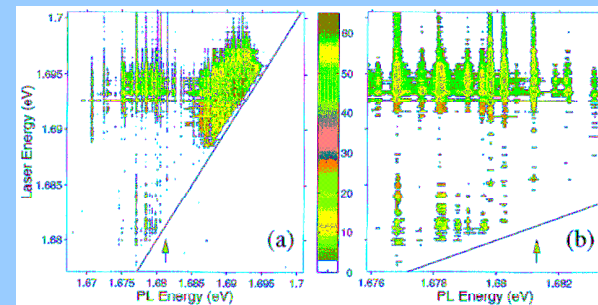
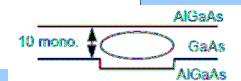
VOLUME 76, NUMBER 16

PHYSICAL REVIEW LETTERS

15 APRIL 1996

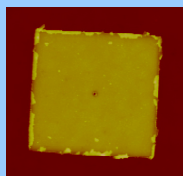
### Fine Structure Splitting in the Optical Spectra of Single GaAs Quantum Dots

D. Gammon, E. S. Snow, B. V. Shanabrook, D. S. Katzer, and D. Park  
Naval Research Laboratory, Washington, D.C. 20375-5347  
(Received 17 August 1995)

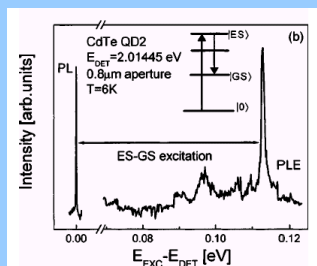
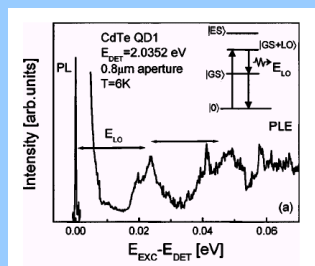




## Spektroskopia rezonansowa



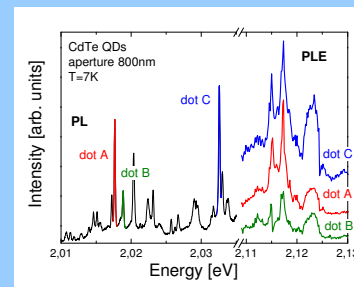
dwa typy rezonansów obserwowane dla kropek kwantowych



CdTe/ZnTe QDs  
T. Nguyen, SM, *et al.*, PRB 2004



## Podobieństwo widm PLE



widma PLE wskazują na występowanie identycznych rezonansów dla różnych kropek kwantowych w zespole

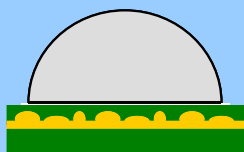
T. Nguyen, SM, *et al.*, PRB 2007



## Obrazowanie luminescencji

better spatial resolution

improved signal to noise ratio



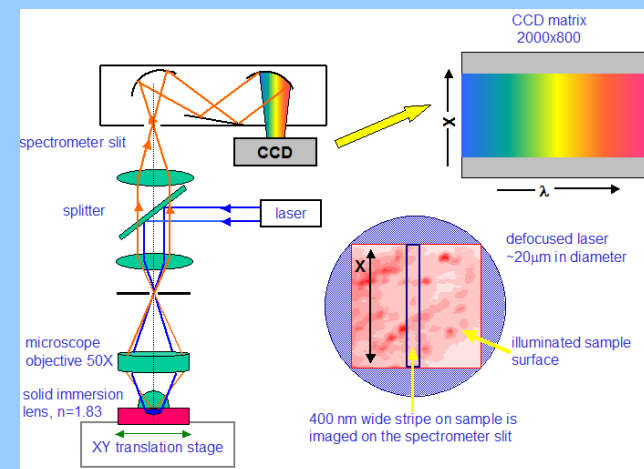
increase of the refractive index between the microscope and the sample increases the effective numerical aperture of the system

enhanced collection efficiency

should enable large field mapping usable at low temperature  
easy to fabricate, materials used:  
- zirconium dioxide,  $n=2$   
- gallium phosphide,  $n=3.5$   
- Schott glass,  $n=1.8$



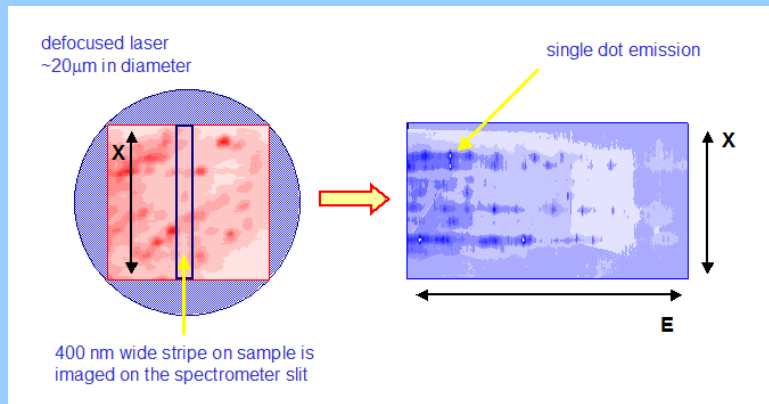
## Obrazowanie luminescencji



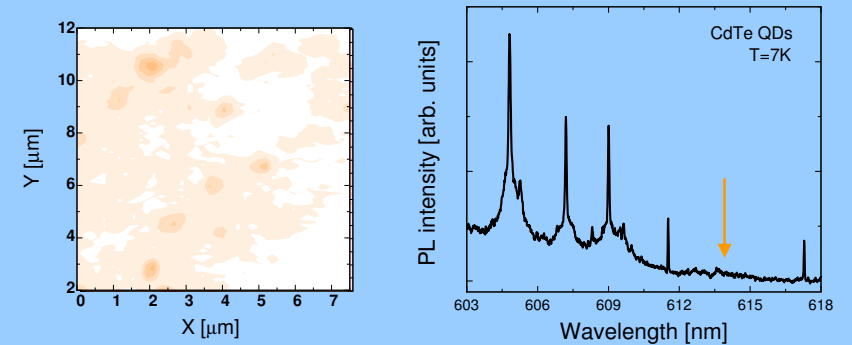
K. Hewaparakrama, SM, *et al.*, APL 2004



## Obrazowanie luminescencji



## Mapowanie luminescencji

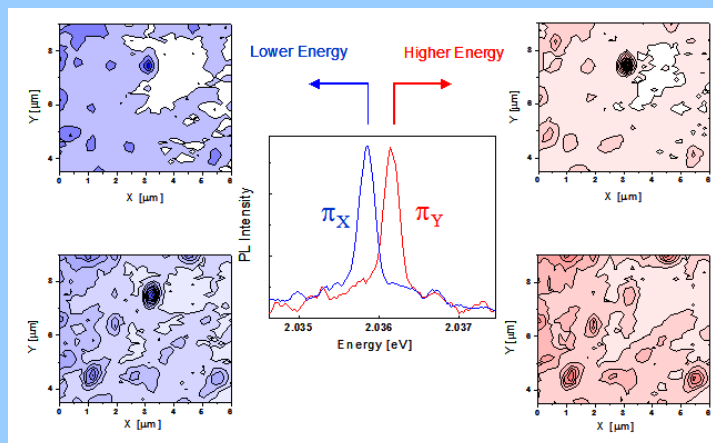


for each emission energy a PL an  $\sim 8 \times 8 \mu\text{m}$  map is collected  
approximately  $10^5$  individual dots can be imaged with a very high signal to noise ratio in a single  $\frac{1}{2}$  hour acquisition

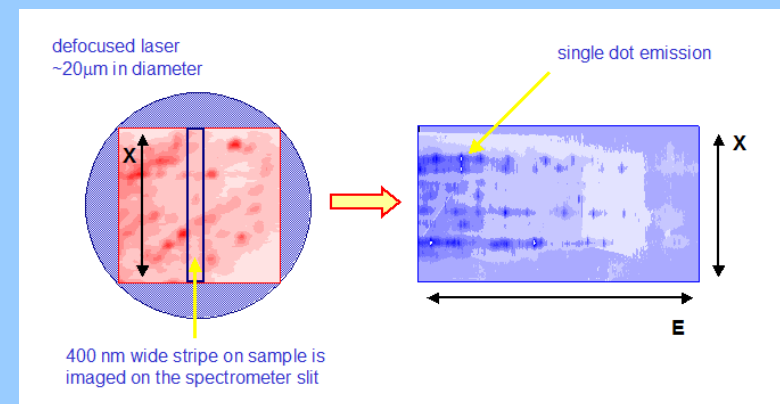
K. Hewaparakrama, SM, *et al.*, APL 2004



## Mapowanie luminescencji

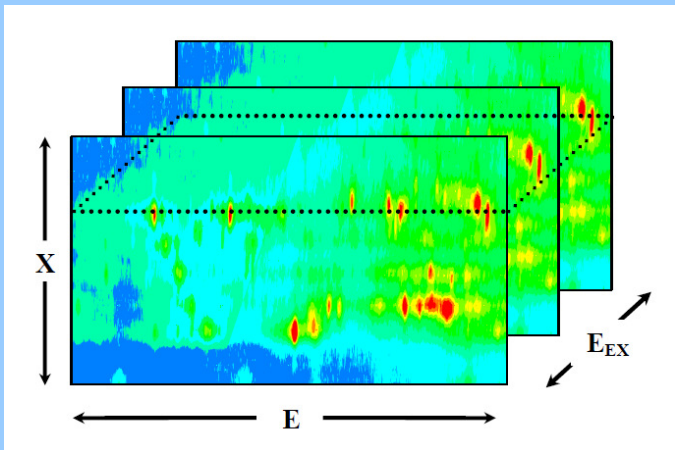


## Mapowanie rezonansów

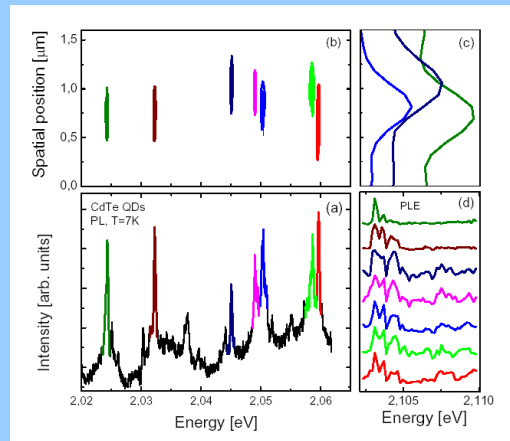




# Mapowanie rezonansów



# Mapowanie rezonansów



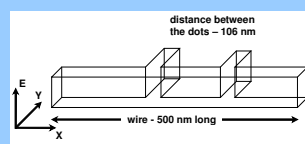
identyczne rezonanse występują dla kropek o różnym położeniu

T. Nguyen, SM, et al., PRB 2007

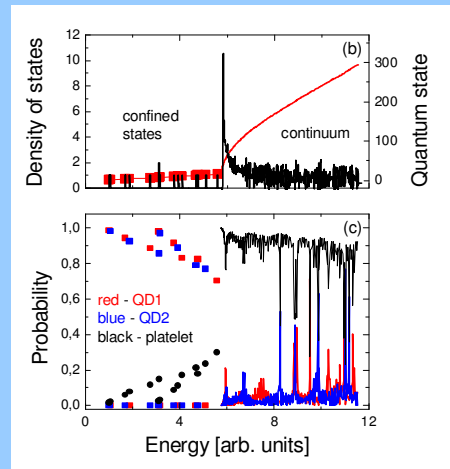


# Model układu

druk łączący dwie kropki kwantowe



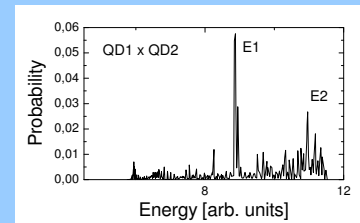
stany związane są wyraźnie oddzielone od stanów ciągłych



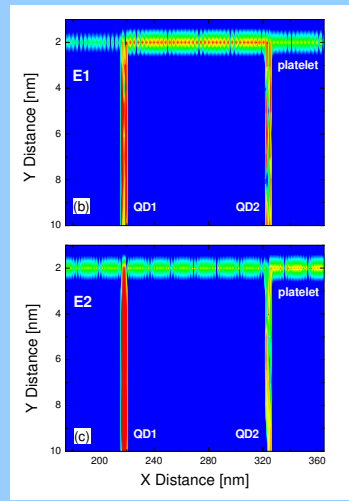
T. Nguyen, SM, et al., PRB 2007



# Model układu



wzbudzenie placka umożliwia obsadzenie obu kropek kwantowych



T. Nguyen, SM, et al., PRB 2007