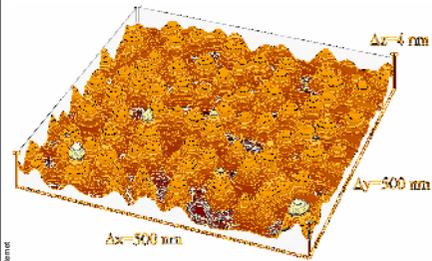


Miniaturyzujemy!



- Półprzewodniki
- a. Studnie
 - i. Studnie i ekscytony
 - ii. Lasery
 - iii. Dwuwymiarowe gazy
 - b. Druty
 - i. Półprzewodniki
 - ii. Organika
 - iii. Laser z drutów
 - c. Kropki
 - i. Kropki planowane i nie
 - ii. Tranzystor na pojedynczym elektronie

Jacek Szczytko, Wydział Fizyki UW

Struktury niskowymiarowe Low-dimensional Semiconductor Systems

Studnie kwantowe

2D

Druty kwantowe

1D

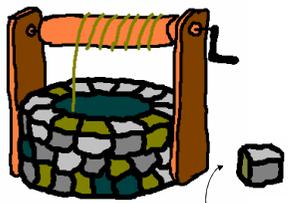
Kropki kwantowe

"0D"
DISCRETE ELECTRONIC STRUCTURE

Jacek.Szczytko@fuw.edu.pl

Hubert J. Kenner

Studnia Kwantowa



studnia kwantowa

Jacek.Szczytko@fuw.edu.pl

Prof. Andrzej Twardowski

Cząstka w studni potencjału

Warunek $kL = n\pi \Rightarrow k = n\frac{\pi}{L} \quad n=1,2,3\dots$

oznacza, że wektor falowy może przyjmować tylko niektóre wartości, czyli że jest **skwantowany**

podobnie energie są **skwantowane**:

$$E = \frac{\hbar^2 k^2}{2m} = \left(\frac{\hbar^2 \pi^2}{2mL^2} \right) n^2$$

Prawdopodobieństwo
(kwadrat funkcji falowej)

* „klasyczna” cząstka w studni mogłaby mieć dowolne energie i przebywać w dowolnym miejscu studni.

Jacek.Szczytko@fuw.edu.pl

Prof. Andrzej Twardowski

Cząstka w studni skończonej

Jacek.Szczytko@fuw.edu.pl

W przypadku studni skończonej też jest kwantyzacja energii (ale są też energie nieskwantowane).

energia [eV]
 — energia nieskwantowana
 — szczyłek studni
 $E_3 = 280 \text{ eV}$
 $E_2 = 109 \text{ eV}$
 $E_1 = 24 \text{ eV}$

Funkcja falowa rozciąga się poza barierę!

Cząstka może wnikać w barierę!

Zasadnicza różnica: Klasyczna cząstka nie może wnikać w barierę.

The thick solid curves are the wave functions, (0) the ground state, (1) the first excited state.

MBE

Jacek.Szczytko@fuw.edu.pl

Quantum Well

MBE → Osadzanie z atomową precyzją warstw o różnym składzie lub domieszkowaniu

2D

Hubert J. Krenner

Studnia Kwantowa

Inżynieria przerwy energetycznej

Jacek.Szczytko@fuw.edu.pl

TEM J.Jasiński

A. Babiński

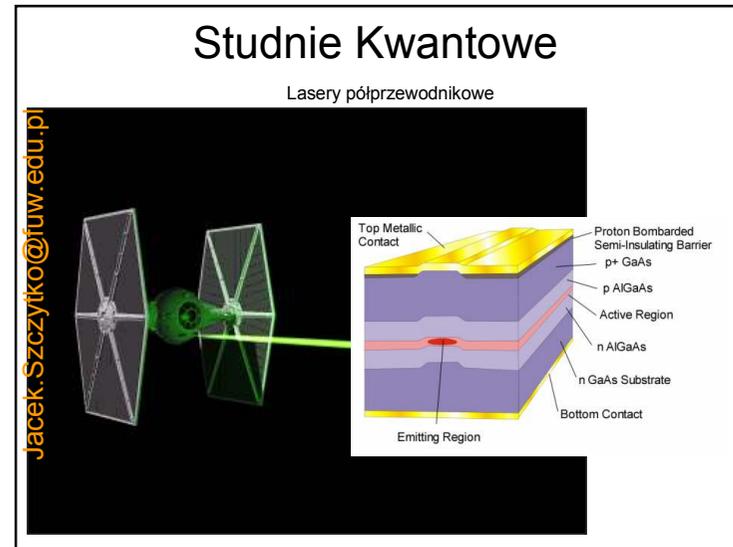
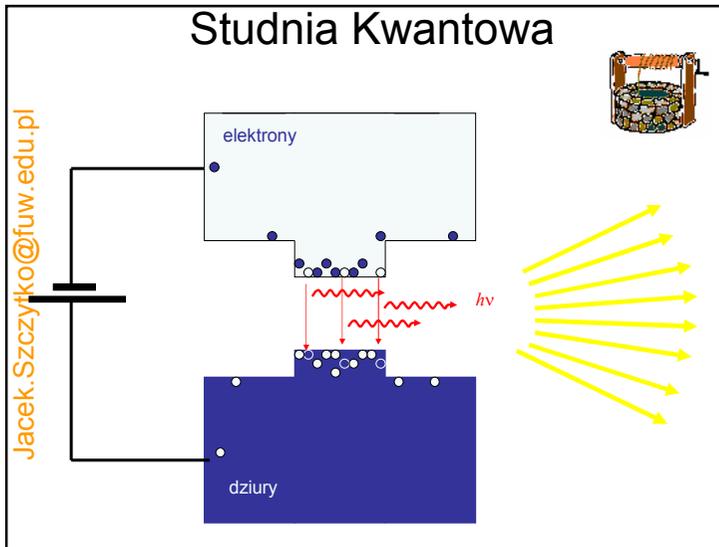
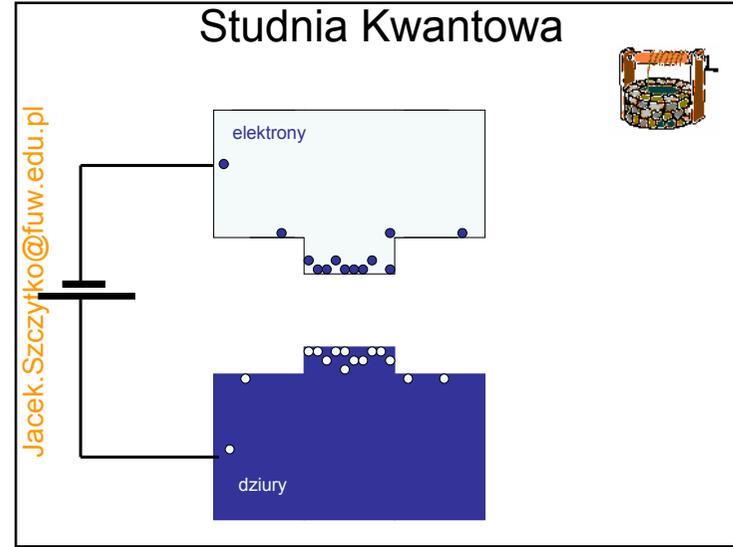
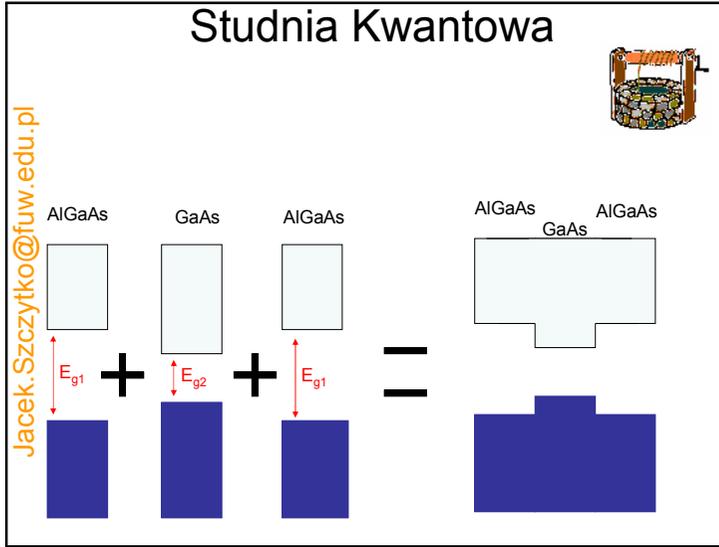
Teoria pasmowa ciał stałych.

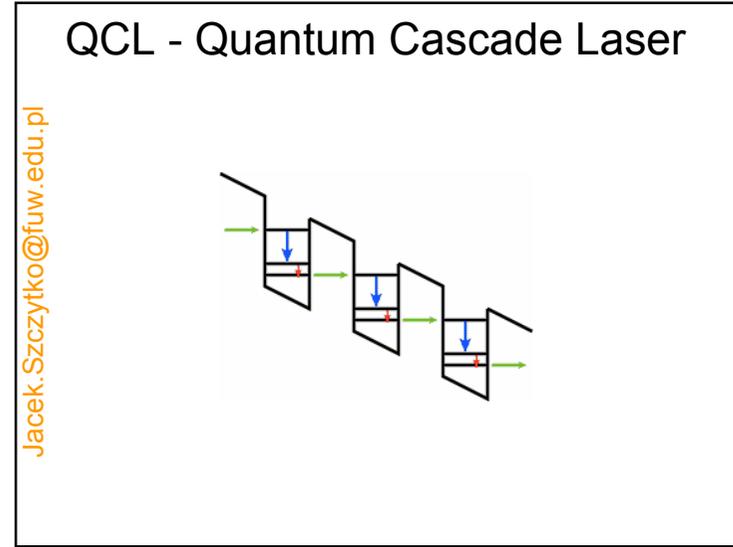
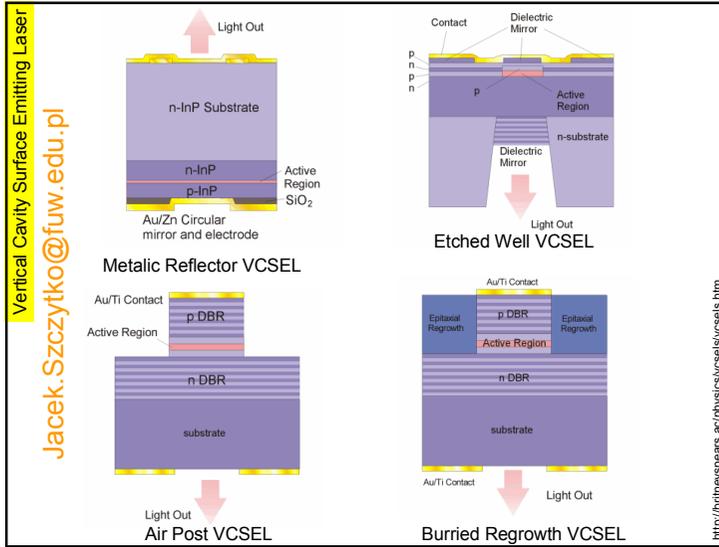
Jacek.Szczytko@fuw.edu.pl

ENERGIA ELEKTRONOW

metale półprzewodnik izolator

Jak zobaczyć przerwy?





QCL - Quantum Cascade Laser

Jacek.Szczytko@fuw.edu.pl

The top part shows an energy band diagram for a QCL structure with layers of AlAs, In_{0.53}As, InAs, and MINIGAP. The bottom part shows two photographs of QCL components:

- The QUANTA® OEM module (LASER COMPONENTS)
- A photograph of a QCL Laser Head.

http://www.sacher-laser.com/QCL_LaserHead.php

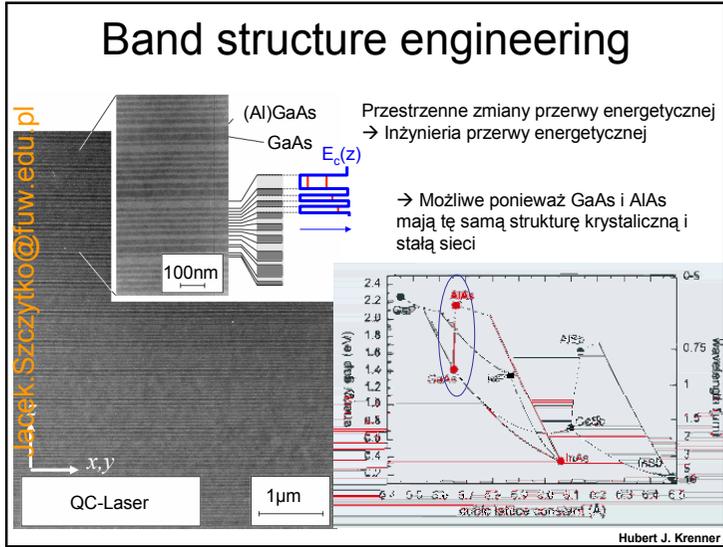
QCL - Quantum Cascade Laser

Jacek.Szczytko@fuw.edu.pl

The top part shows an energy band diagram for a QCL structure with layers of Al_xIn_{1-x}As, AlAs, InAs, and MINIGAP. The diagram is labeled with F = 75 kV/cm. The bottom part shows two photographs of QCL components:

- The QUANTA® OEM module (LASER COMPONENTS)
- A photograph of a QCL Laser Head.

http://www.sacher-laser.com/QCL_LaserHead.php



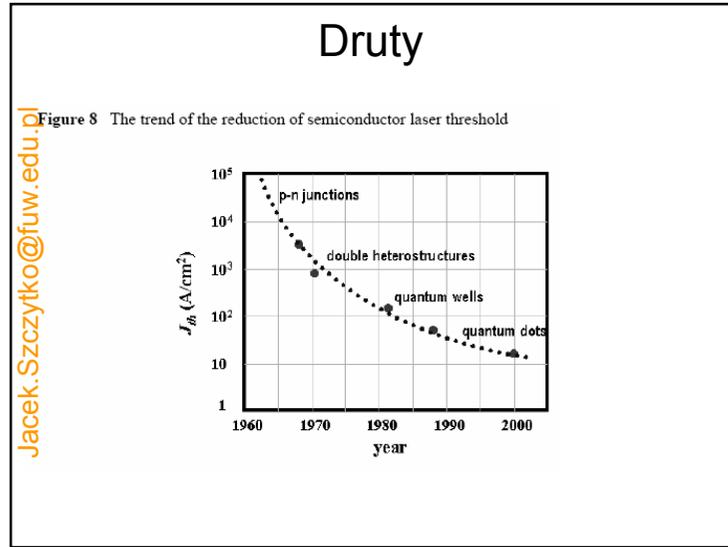
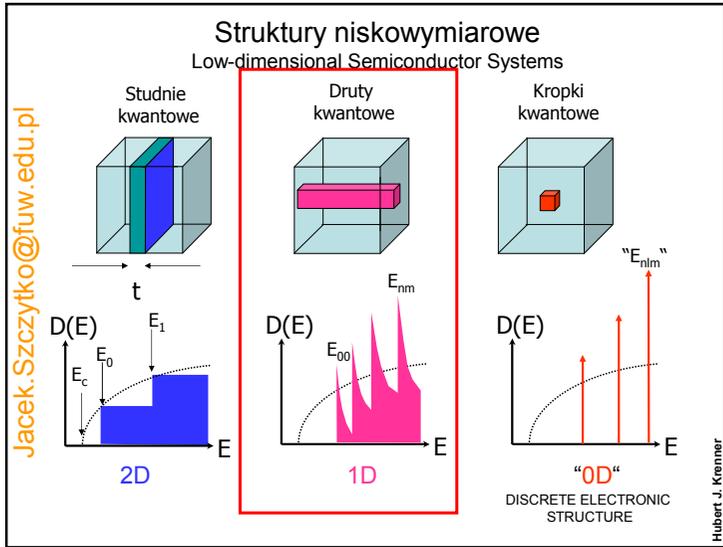
Studnie Kwantowe

Więcej: <http://britneyspears.ac/lasers.htm>

Conduction Band

Valence Band

Hubert J. Krenner



Druty

PHYSICAL REVIEW B VOLUME 52, NUMBER 15 15 OCTOBER 1995-1

Dimensionality effects on strain and quantum confinement in lattice-mismatched InAs, P_{1-x}/InP quantum wires

M. Notomi*
NTT Opto-electronics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-01, Japan

J. Hammersberg and H. Weman
Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden

S. Nojima, H. Sugiura, M. Okamoto, and T. Tamamura
NTT Opto-electronics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Ka

M. Potemski
Grenoble High Magnetic Field Laboratory, Max-Planck Institute für F and Centre National de la Recherche Scientifique, 38042 Greno
(Received 29 March 1995)

FIG. 1. Fabrication process of strained InAsP/InP quantum wires.

Druty

Figure 11 Growth of quantum wires on a vicinal surface with multiatomic steps

Figure 12 Selective growth of quantum wires on a pre-patterned V-groove substrate

Druty

Figure 9 Quantum wire fabrication based on nanoscale etching and re-growth

Figure 10 Formation of one-dimensional nanoscale quantum wires by strain-induced lateral ordering

Druty

Figure 13 Selective growth of quantum wires on a pre-patterned Λ -ridge substrate

Figure 14 Formation of one-dimensional T-intersection quantum wire structure by cleaved-edge overgrowth

Jacek.Szczytko@fuw.edu.pl

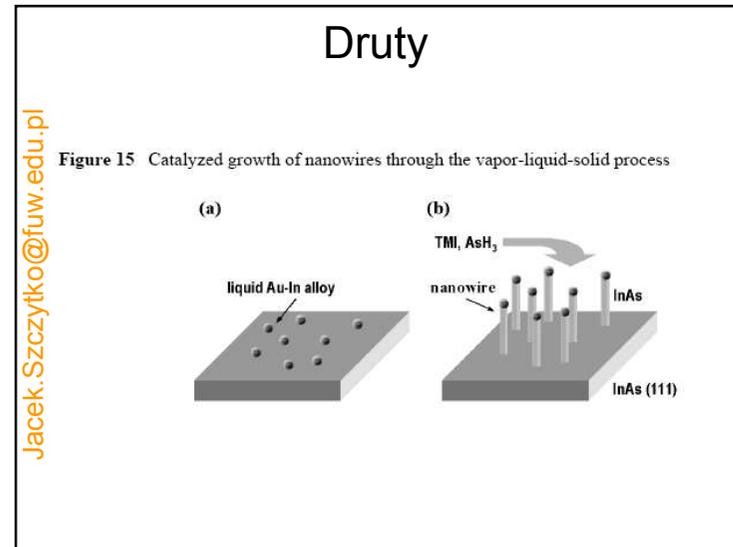
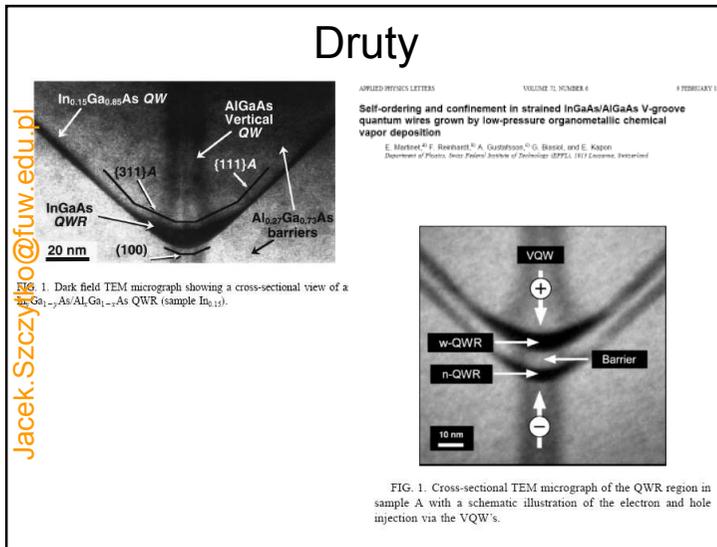
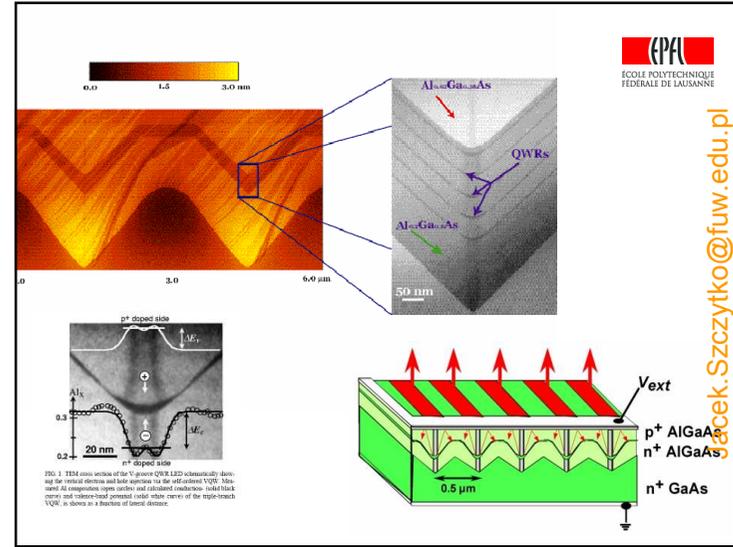
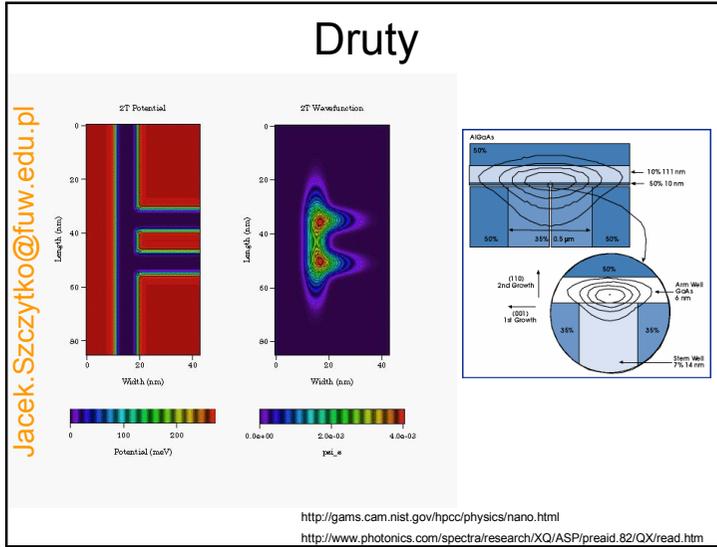
42 Int. J. of Nanotechnology, Vol. 1, No. 1/2, 2004
Nanolasers: Lasing from nanoscale quantum wires
Samuel S. Mao

Jacek.Szczytko@fuw.edu.pl

42 Int. J. of Nanotechnology, Vol. 1, No. 1/2, 2004
Nanolasers: Lasing from nanoscale quantum wires
Samuel S. Mao

Jacek.Szczytko@fuw.edu.pl

42 Int. J. of Nanotechnology, Vol. 1, No. 1/2, 2004
Nanolasers: Lasing from nanoscale quantum wires
Samuel S. Mao



Druty

P.X. Gao et al. / Chemical Physics Letters 408 (2005) 174-178

175

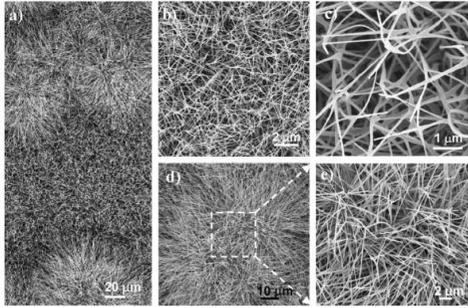


Fig. 1. (a) A typical low magnification SEM image of the as-grown networks of ZnO nanowires and nanorods consisting two o types of morphologies, as indicated by area b (b,c) and c (d,e). (b,c) Enlarged SEM images of uniform networks of ZnO nanowires and nanorods. (d,e) Enlarged SEM images of clumps of nanowires showing the interconnected nanowires and nanorods.

Druty

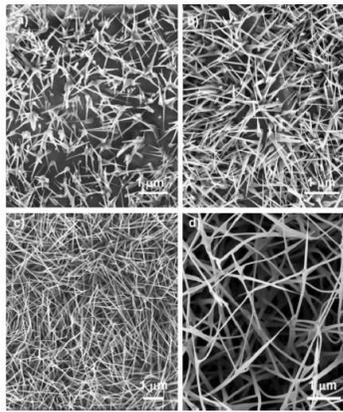


Fig. 5. Formation process of the 3D network. (a) The initial stage of interconnected nanorods growth. (b) The first layer of networking between short nanowires and nanorods. (c) The beginning of the second layer of networking. (d) Highly magnified SEM image giving a clear description about the 3D ZnO networks with mesh space around $2 \times 2 \times 2$ (μm).

Druty

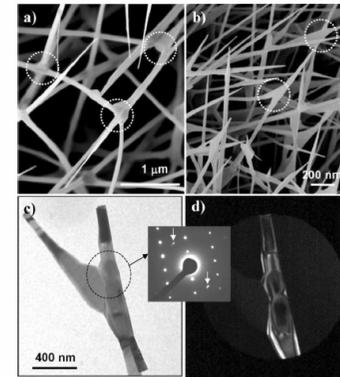


Fig. 4. (a,b) Interconnection types of ZnO nanowires in the nano-network. (c,d) Bright-field and dark-field TEM images of two nanowires interconnected with each other, indicating that the two nanowires are single crystals but they have no orientation relationship. The circle area is used for recording the selected area electron diffraction pattern (inset).

Druty

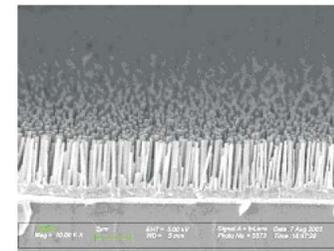


Figure 3. Si/SiO₂/Ti/Pt/ZnO/Nanowire.

Tamkang Journal of Science and Engineering, Vol. 7, No 3, pp. 135-138 (2004)

135

Growth and Patterning of ZnO Nanowires on Silicon and LiNbO₃ Substrates

T. K. Shing*, H. H. Pan, I.-C. Chen and C. I. Kuo

12 Jan. 2 of Nanotechnology, Vol. 7, No. 72, 2004

Druty

Nanolasers: Lasing from nanoscale quantum wires

Samuel S. Mao

Laserowanie bez wnęki (t.j. sam nanodrut jest dla siebie wnęką!)

Jacek.Szczytko@fuw.edu.pl

Druty

Conductance measurements on lambda DNA fragments

Fragments of lambda DNA with a length of 1.5 micron (4500 base pairs) were deposited on gold electrodes spaced by about 250 nm. By AFM imaging single DNA molecules were found between the electrodes. The measured resistance between the electrodes was found to be larger than 200 GOhm. Below is an AFM image of DNA over gold electrodes.

D. Porath, A. Bezryadin, S. de Vries, and C. Dekker *Direct measurement of electrical transport through DNA molecules* Nature 403, 635 (2000)

Jacek.Szczytko@fuw.edu.pl

Struktury niskowymiarowe

Low-dimensional Semiconductor Systems

Studnie kwantowe

2D

Druty kwantowe

1D

Kropki kwantowe

"0D"

DISCRETE ELECTRONIC STRUCTURE

Hubert J. Krenner

Jacek.Szczytko@fuw.edu.pl

Jacek.Szczytko@fuw.edu.pl

<http://qt.tn.tudelft.nl/research/qdots/>

Kropki

- Co to są Kropki Kwantowe - Quantum Dots (QD)
- W jaki sposób je się wytwarza
 - Nanotechnologia
 - Samoorganizujące się Kropki Kwantowe (Self-assembled Quantum Dots)

Textbook:

"Mesoscopic region in a semiconductor surrounded by higher band gap material"

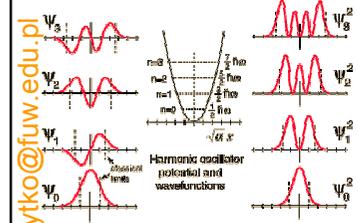
- Pełna kwantyzacja stanów
- gęstość stanów funkcji δ Diraca
- Wąskie widma spektralne w emisji i absorpcji
- „Sztuczne atomy” - “Artificial Atoms”

Jacek.Szczytko@fuw.edu.pl

Jacek.Szczytko@fuw.edu.pl

Kropki kwantowe - lokalizacja w płaszczyźnie wzrostu

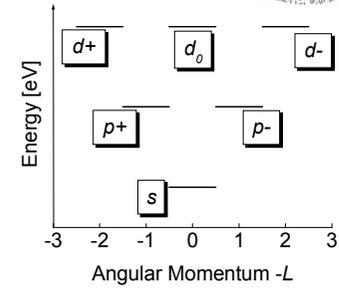
Jacek.Szczytko@fuw.edu.pl



$$V_{\beta}(x, y) = \frac{1}{2} m_{\beta}^* \omega_{\beta}^2 (x^2 + y^2)$$

gdzie, $\beta = e, h$

$$E_{\beta, n, m} = \hbar \omega_{\beta} (n + \frac{1}{2}) + \hbar \omega_{\beta} (m + \frac{1}{2})$$



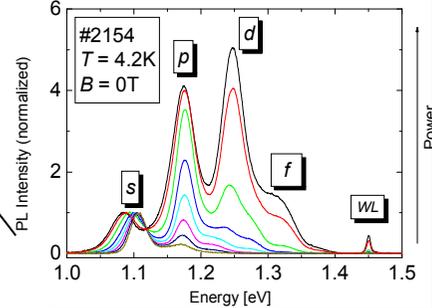
$n, m = 0, 1, 2, \dots$
 $L = n - m$ (elektron)

Adam Babiński

Kropki kwantowe – sztuczne atomy

Model oscylatora harmonicznego:

- powłoki s-, p-, d-, ...
- Dozwolone przejścia optyczne

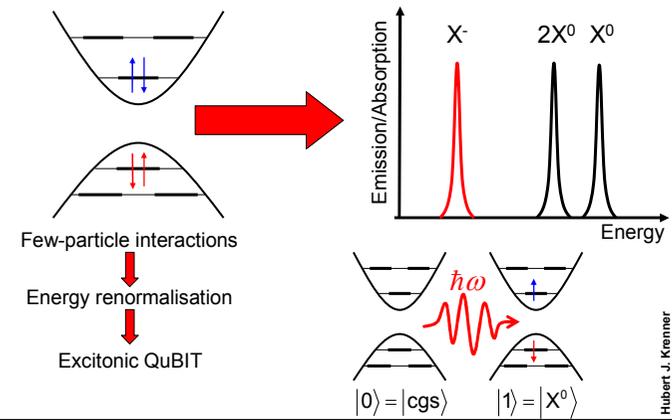


Luminescencja z dużego zbioru QDs w funkcji mocy pobudzenia ($\lambda_{exc} = 514.5$ nm)

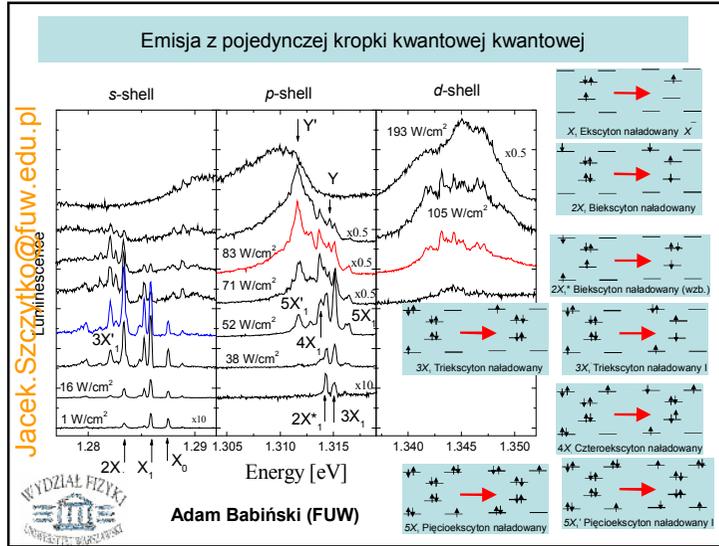


Oddziaływania wielociałowe

Jacek.Szczytko@fuw.edu.pl



Hubert J. Krenner



Rodzaje kropek kwantowych

"Klasyczne" kropki kwantowe

"Egzotyczne" Kropki kwantowe

Exciton

Nanocrystals

Specjalne techniki wzrostu

Jacek.Szczytko@fuw.edu.pl

Hubert J. Kenner

Electrostatically defined Quantum Dots

Two-dimensional electron system

Depletion by gate electrodes

Quantum Dots:
Attractive confinement for electrons

Hubert J. Kenner

Jacek.Szczytko@fuw.edu.pl

Blokada Kulombowska

source island drain

V_{SD} V_g I_{SD}

Hubert J. Kenner

Jacek.Szczytko@fuw.edu.pl

<http://people.cmr.cornell.edu/~ralph/projects/metalset/>

Kropki

Silicon Single Electron Transistor
(After Gate Oxidation)

10 nm

032883 5.0k X200k 150nm

Silicon Single Electron MOS Memory
(Before Oxidation)

Polysilicon Dot

Silicon Channel

071507 4.0k X150k 200nm

NanoStructure Lab
UNIVERSITY OF MINNESOTA

Jacek.Szczytko@fuw.edu.pl

Kropki

1 μm

2DEG

superconducting quantum dots

A series of superconducting aluminum disks (0.1 to 2 microns in size) sit on top of a semiconducting structure. Buried beneath the spots where the strips cross are tiny realms in which electrons, constituting 2-dimensional electron gases (2DEG), are sensitive to the magnetization of the disks above. In this way the size-dependent properties of superconductors no bigger than a Cooper pair (the electron doublets that form inside superconductors) can be studied.

Jacek.Szczytko@fuw.edu.pl

Positioning Quantum Dots – Patterned Substrate

Zhong *et al.*, APL **84**, 1922 (2004)

Lithographically defined Diffusion

MBE defined Diffusion or Strain

Jochen Bauer

AlAs/GaAs superlattice

InGaAs layers

Distance (μm)

Distance (μm)

Distance (nm)

Height (nm)

Wasserman *et al.*, APL **85**, 5352 (2004)

Jacek.Szczytko@fuw.edu.pl

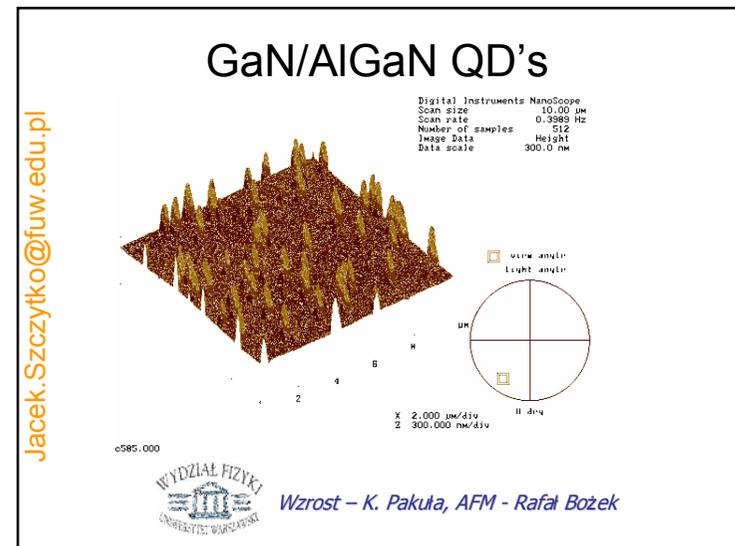
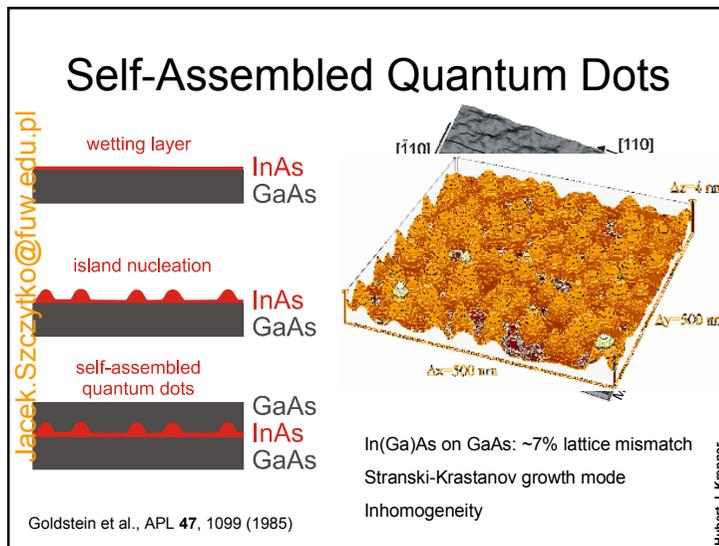
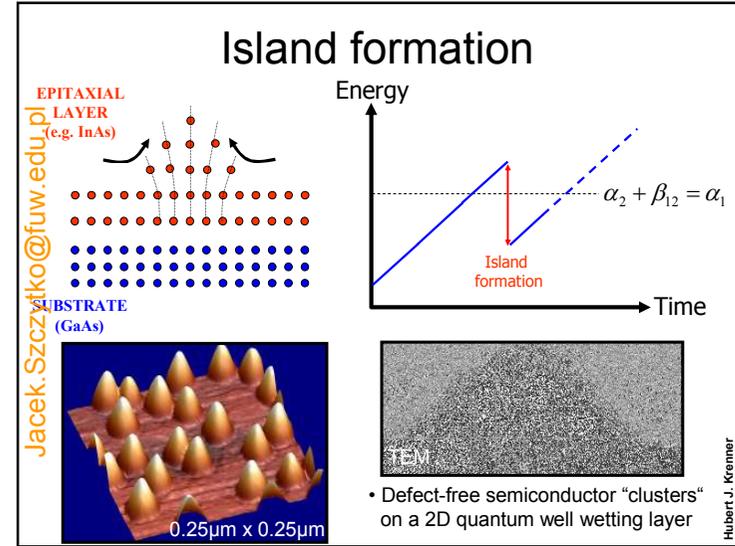
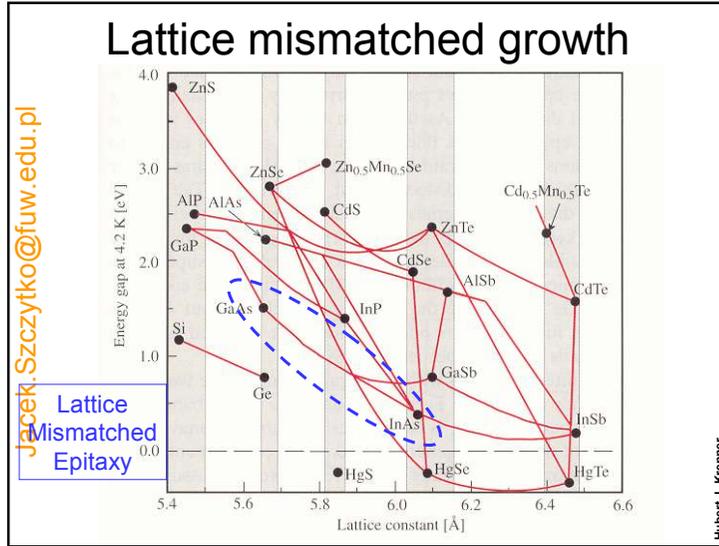
Hubert J. Krenner

Quantum Dot

Hubert J. Krenner

Walter Schottky Institut and Physik Department E24, TU München

Jacek.Szczytko@fuw.edu.pl



Jacek.Szczytko@fuw.edu.pl

Doświadczenie

$T=300K$
Minimum step~50 nm
Maximum step~1 μm

$T=4.2K$
Minimum step~5 nm
Maximum step~100 nm

Single mode fiber -
mode field diameter
Collection (600 μm) 5.5 μm

0.2-1 μm

300 μm

A.Babinski, et al. Physica E 26 (2005) 190
FUW Hoża 69

Jacek.Szczytko@fuw.edu.pl

Access to individual QDs

sample
7mm
laser beam

Emission spectrum

CdTe/ZnTe

Intensity [a.u.]

Photon energy (eV)

prof. J. A. Gaj
prof. M. Nawrocki
dr hab. A. Golnik
dr P. Kossacki

mgr W. Maślana
mgr J. Suffczyński
mgr K. Kowalik
mgr W. Pacuski

mgr A. Trajnerowicz
mgr B. Piechal
M. Goryca
T. Kazimierzuk

FUW
Hoża 69

Jacek.Szczytko@fuw.edu.pl

GaN/AIGaN QD's

Energy: 3.22eV

Energy: 3.33eV

Energy: 3.38eV

Energy: 3.34eV

μPL - Barbara Chwalisz et al.

FUW
Hoża 69

Jacek.Szczytko@fuw.edu.pl

GaN/AIGaN QD's

c575

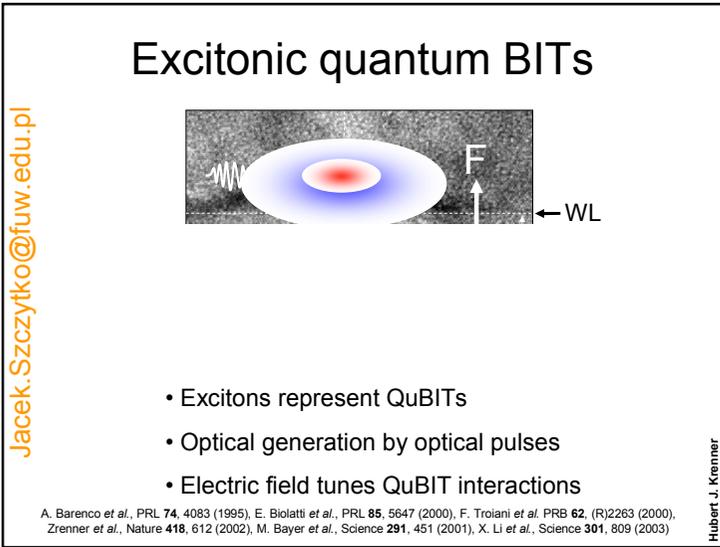
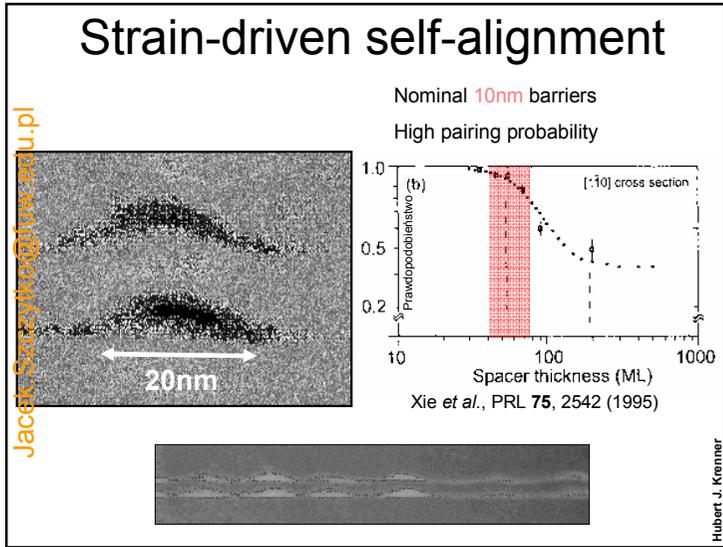
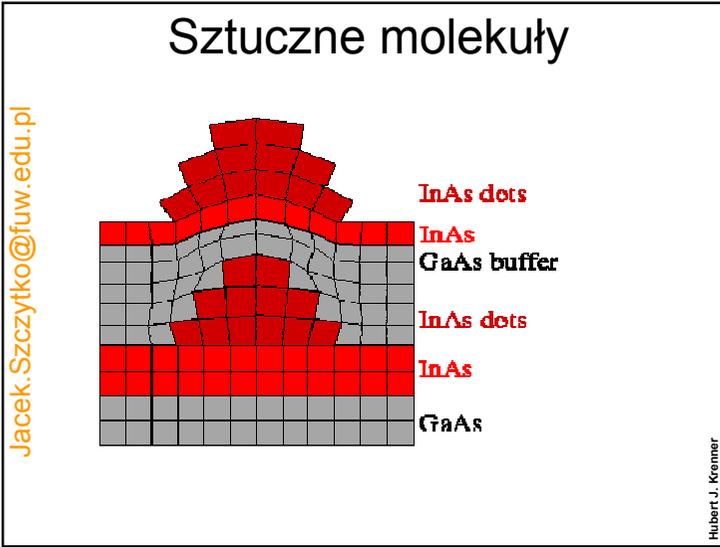
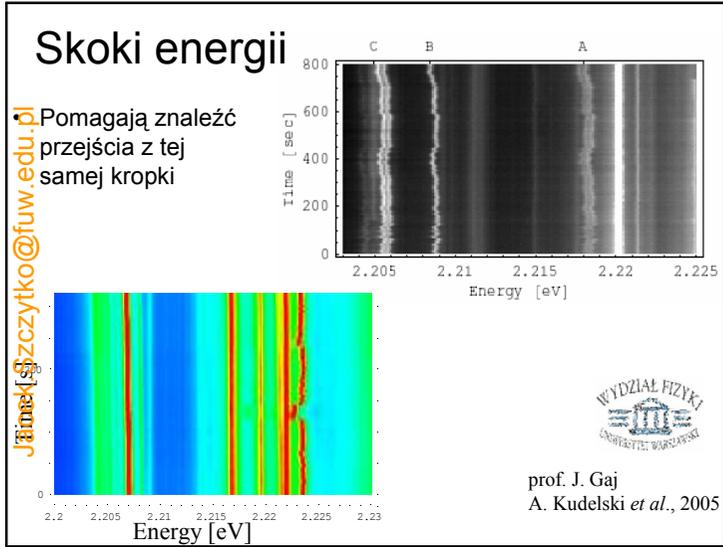
Energy (eV)

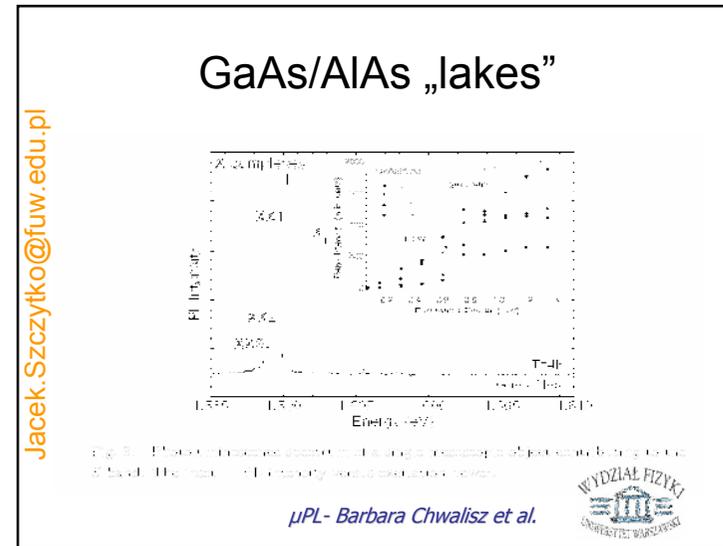
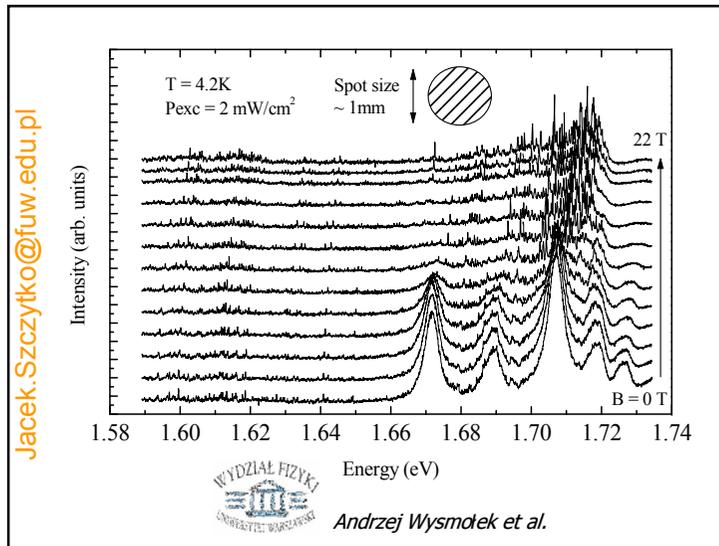
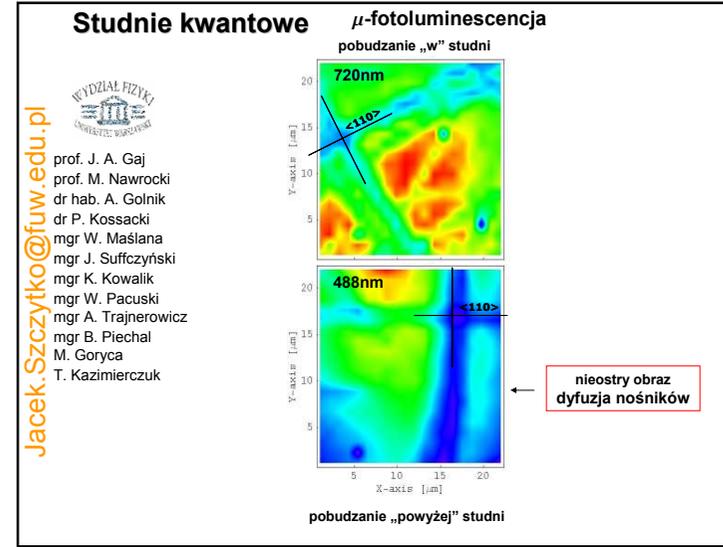
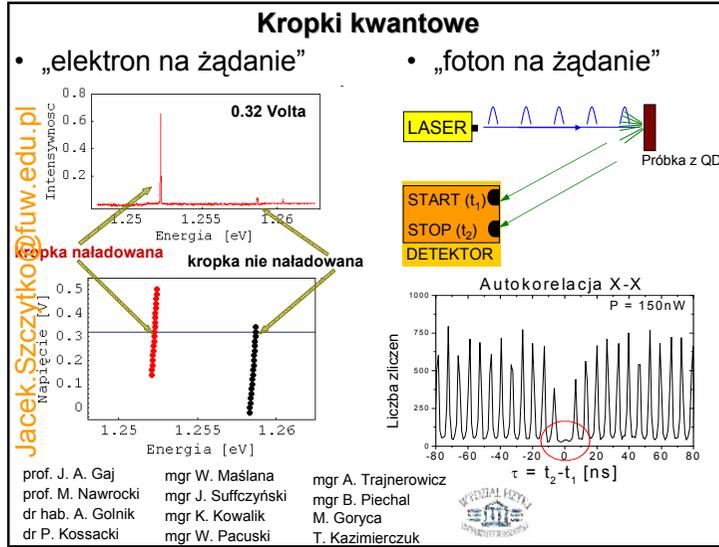
$\Delta E = 7meV$

time 100 X 16s

FUW
Hoża 69

μPL - Katarzyna Surowiecka et al.





Kropki kwantowe + bio

Jacek.Szczytko@fuw.edu.pl

T2-MP EVITAGS
Non-heavy Metal - InP Based, Water Stabilized Quantum Dots

Ternary III-V EviDot
Molecular Plate™ Shell
T2-MP EviTag - InGaP/ZnS with Lipid
CdSe Core EviDot
CdSe/ZnS Core-Shell EviDot

Cd (cadmium)
Se (selenium)
Zn (zinc)
S (sulfur)

A PbSe Quantum Dot as seen through a transmission electron microscope (TEM).

<http://www.evidenttech.com/>

Kropki kwantowe + bio

Jacek.Szczytko@fuw.edu.pl

Double duty. Green quantum dots cling to mitochondria in the cytoplasm; orange ones label proteins in the same cells' nuclei.

Science, Vol 300, Issue 5616, 80-81, 4 April 2003

Kropki kwantowe + bio

Jacek.Szczytko@fuw.edu.pl

Bull's-eye. Red quantum dots injected into a live mouse mark the location of a tumor.

Science, Vol 300, Issue 5616, 80-81, 4 April 2003

Nanotechnologie

Jacek.Szczytko@fuw.edu.pl

Total spend on nanotechnology

Type of company or institution

Type of company or institution	Percentage
Start Up	10%
SME	15%
Large Company or Multinational	31%
Government	8%
Private Research Institute	18%
Academic Institution	18%

Podziękowania

Zakład Fizyki Ciała Stałego <http://www.fuw.edu.pl/~zfcs/>
 prof. dr hab. M. Baj



Struktury Kwantowe GaAs/AlAs

mgr B. Chwalisz Prof. M. Baj
 dr A. Wyszomolka dr hab. D. Wasik
 dr M. Potemski (GHMFL) dr J. Siwiec
 prof. R. Stepniowski

Spektroskopia ultraszybka

prof. J. Gaj,
 prof. M. Nawrocki,
 dr hab. A. Gólnik,
 W. Goryca,
 dr Kazimierzczuk,
 dr P. Kossacki,
 K. Kowalik,
 W. Maślana,
 W. Pacuski,
 B. Piechal,
 J. Suffczyński,
 A. Trajnerowicz

Kropki Kwantowe: GaN/Al_xGa_{1-x}N

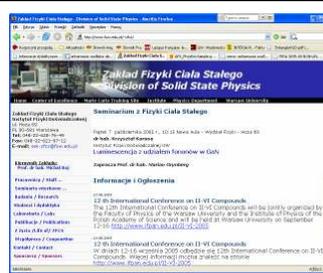
prof. R. Stepniowski
 mgr K. Pakula
 mgr R. Bożek
 mgr K. Surowiecka
 dr A. Wyszomolka
 mgr B. Chwalisz
 prof. J. Baranowski
 dr K. Kossacki
 dr K. Korona
 dr hab. A. Gólnik

Promieniowanie THz

dr Jerzy Lusakowski,
 dr Krzysztof Karpierz,
 mgr Maciej Sakowicz,
 prof. dr hab. Marian Grynberg

Spintronika

prof. dr hab. Maria Kamińska
 prof. dr hab. Andrzej Twardowski
 dr Jacek Gosk
 dr Jacek Szczytko,
 mgr Konrad Działkowski,
 mgr Marcin Zajac



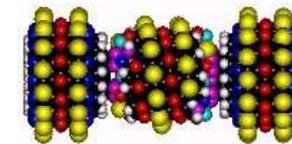
Jacek.Szczytko@fuw.edu.pl

W następnym tygodniu:

Miniaturyzujemy III i IV



1. Miniaturyzujemy III.
 - a. Nanorurki
 - i. Węgiel i nie tylko
 - ii. Pokręcone zasady
2. Nanomaszyny



Jacek.Szczytko@fuw.edu.pl