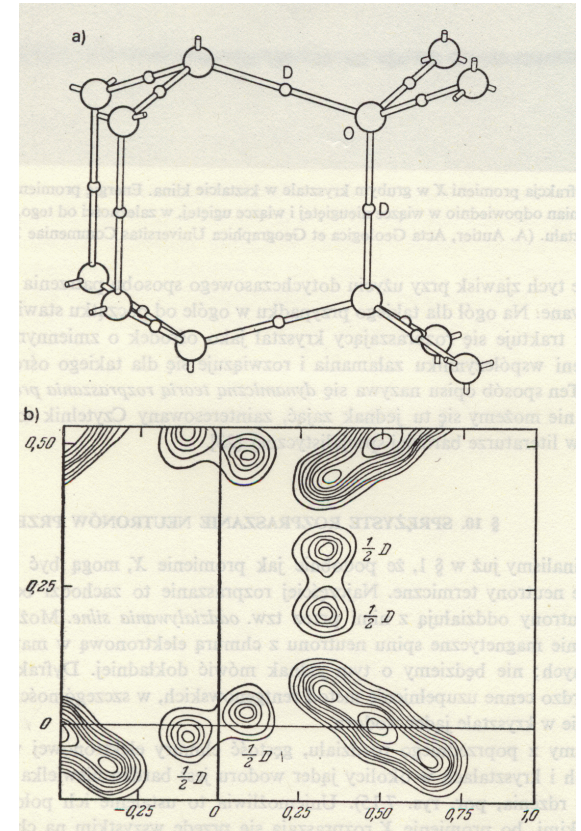
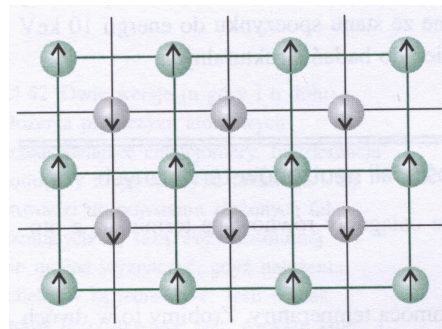
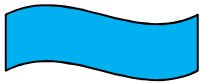


# Fale materii: elektrony, neutrony, lekkie atomy

- ▶ Neutrony – generowane w reaktorze są spowalniane w wyniku zderzeń z moderatorem (grafitem) do  $V = 4 \text{ km/s}$ , co odpowiada energii  $E=0.08 \text{ eV}$  a energia ta odpowiada  $\lambda = 1 \text{ \AA}$
- ▶ Neutrony oddziałują z :
- ▶ jądrami (można wyznaczyć gęstość prawdopodobieństwa znalezienia jąder), wyznaczyć krzywe dyspersyjne fononów
- ▶ momentami magnetycznymi jąder.

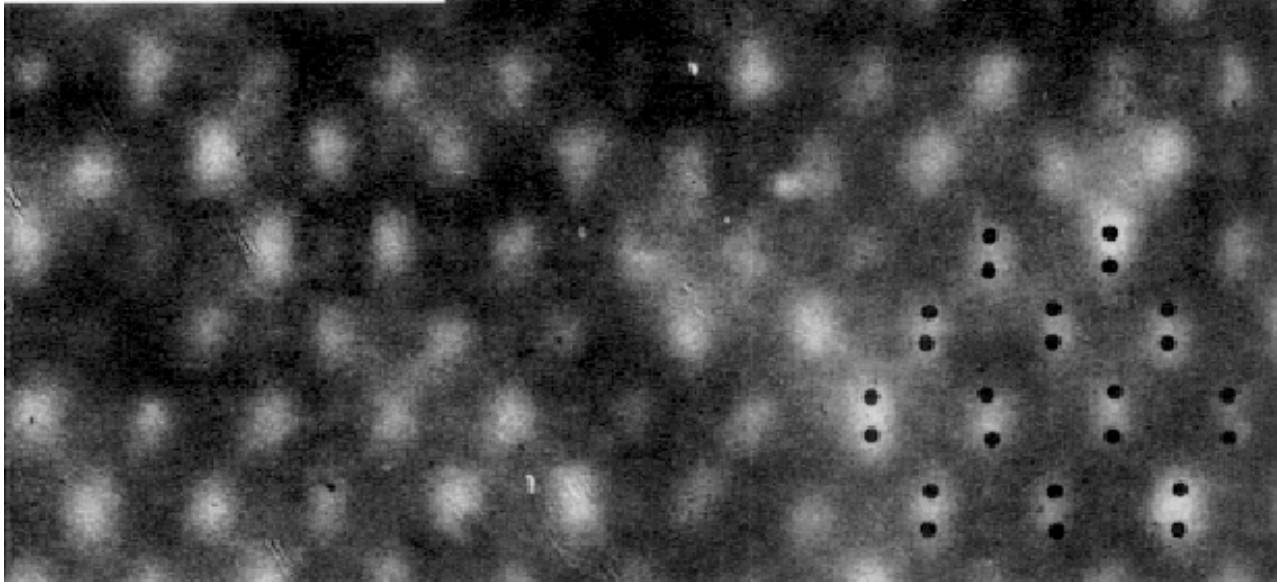
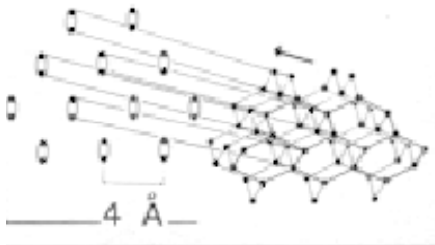


J. Ginter

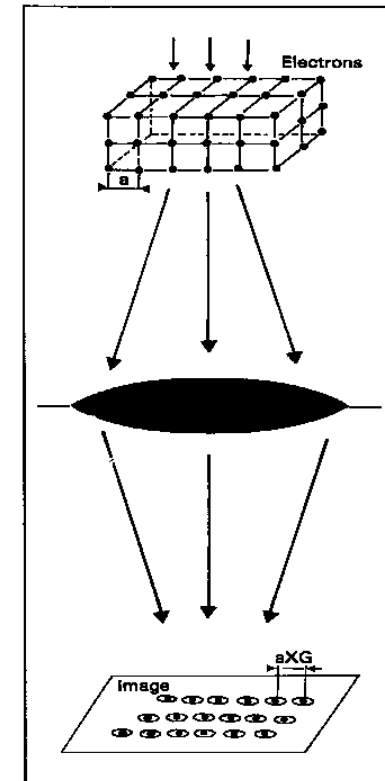


## Wykład 12

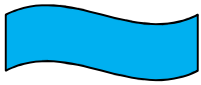
- ▶ Elektrony mają ładunek elektryczny i oddziałują silnie z materią, wnikają bardzo płytko.
- ▶ Zjawisko ugięcia elektronów pozwala na badania strukturalne powierzchni oraz bardzo cienkich warstw



# Elektrony

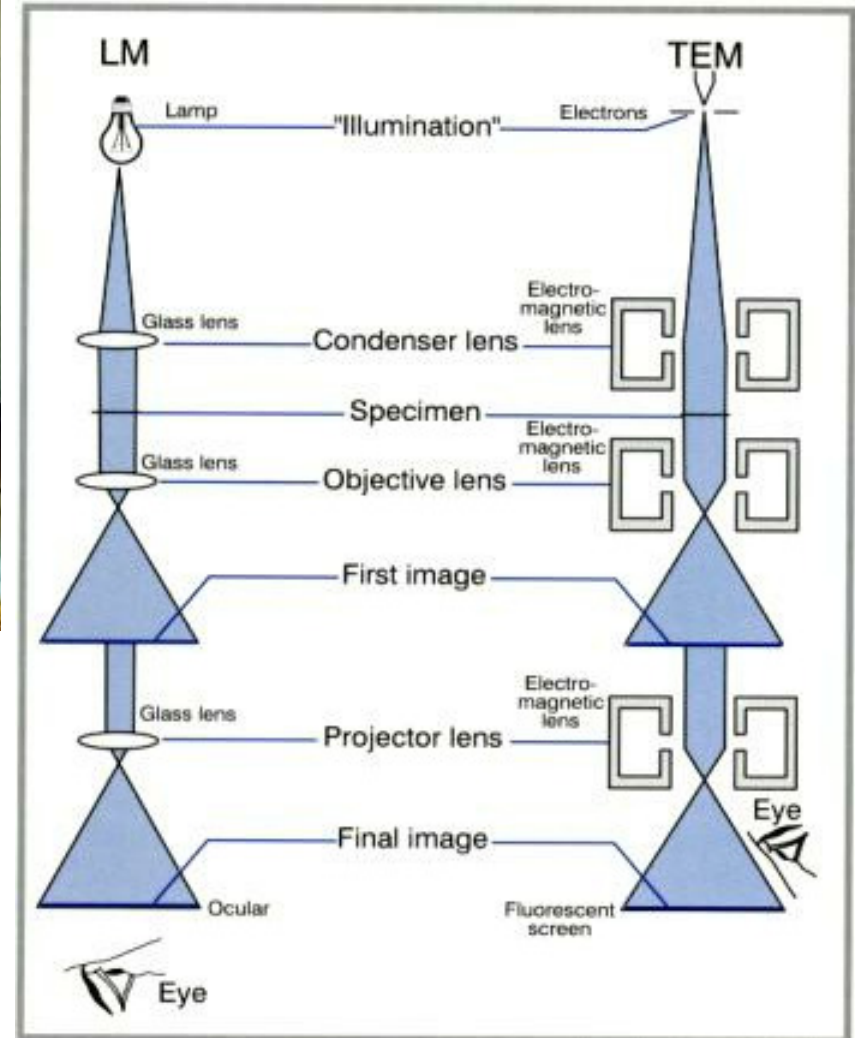


T. Stacewicz & A. Witowski

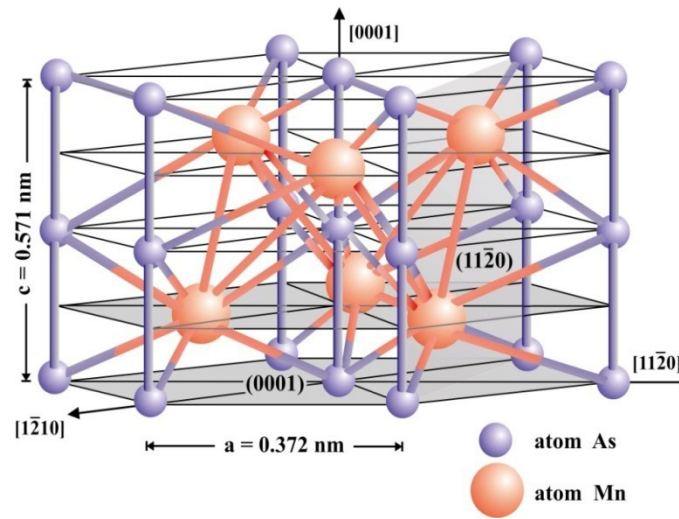
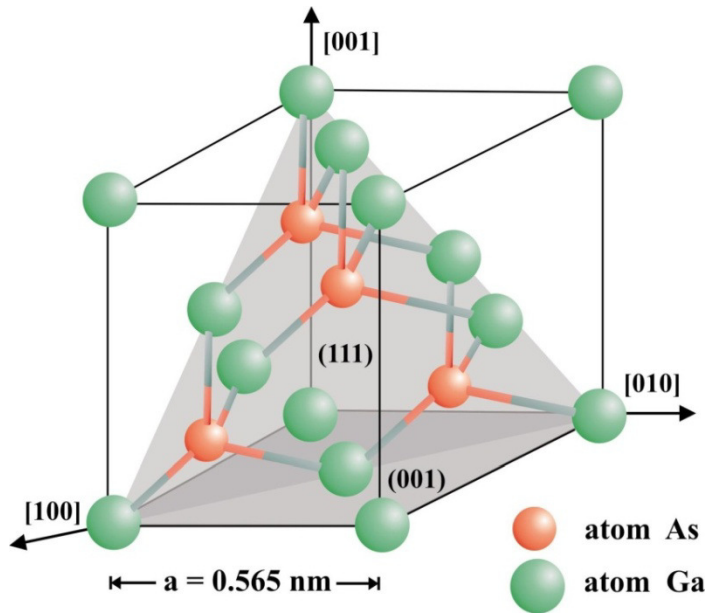


## Wykład 12

# Transmisyjny Mikroskop Elektronowy (TEM)

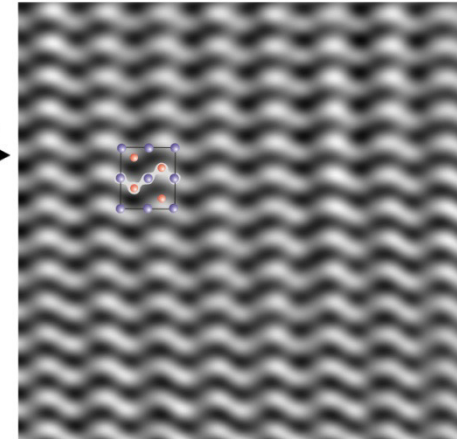


# Transmisyjny mikroskop elektronowy (SEM)

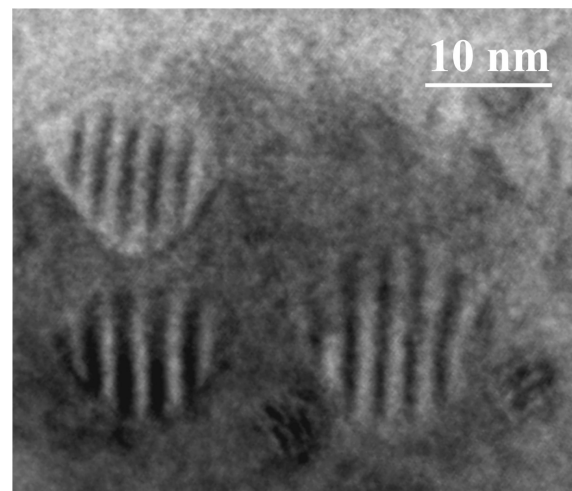
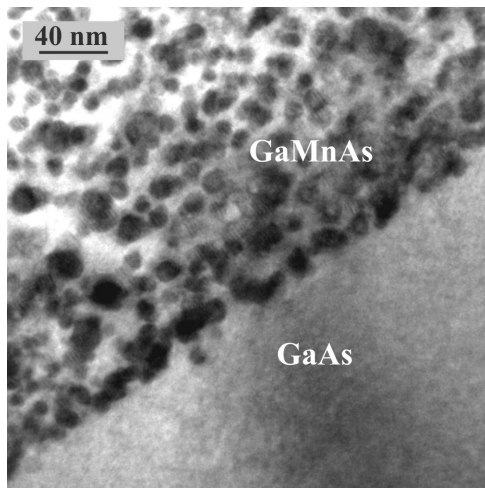
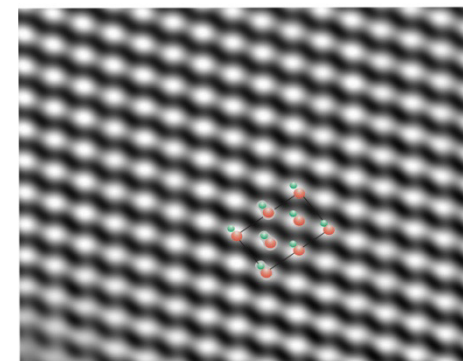


HRTEM  
High Resolution  
TEM)

MnAs - PŁASZCZYZNA (11 $\bar{2}$ 0)



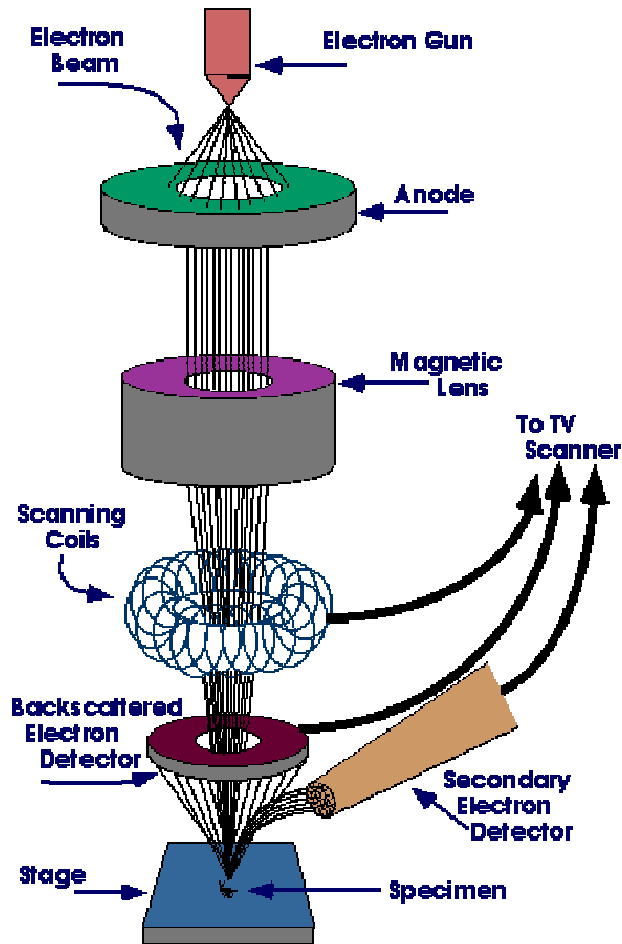
GaAs - PŁASZCZYZNA (11 $\bar{2}$ 0)



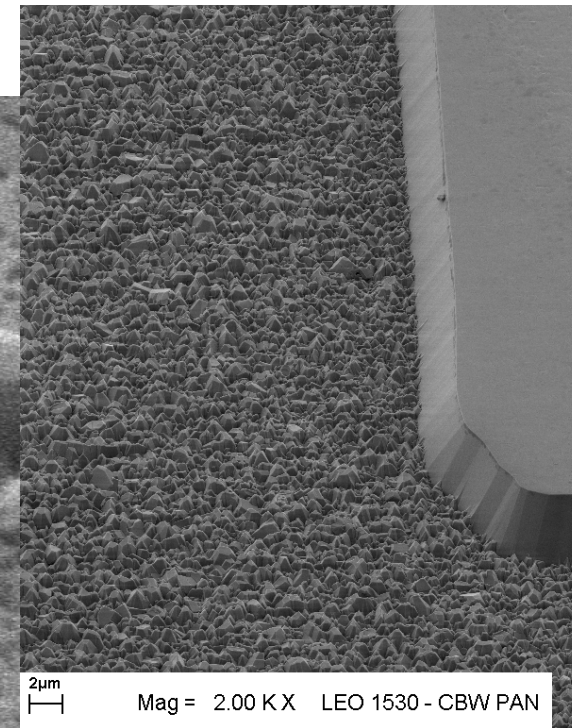
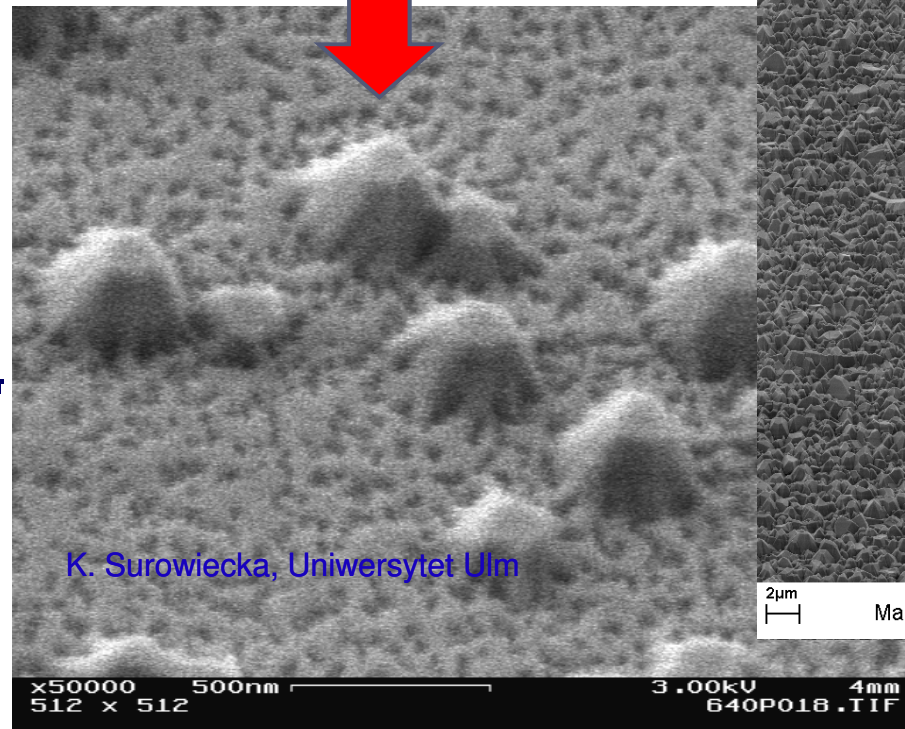
J. Borysiuk

# Skaningowy mikroskop elektronowy (SEM)

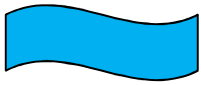
Wykorzystujemy skanowanie powierzchni próbki przez wąską wiązkę elektronów. Elektrony rozpraszają na powierzchni tak jak światło...



Kropki kwantowe GaN/AlGaN

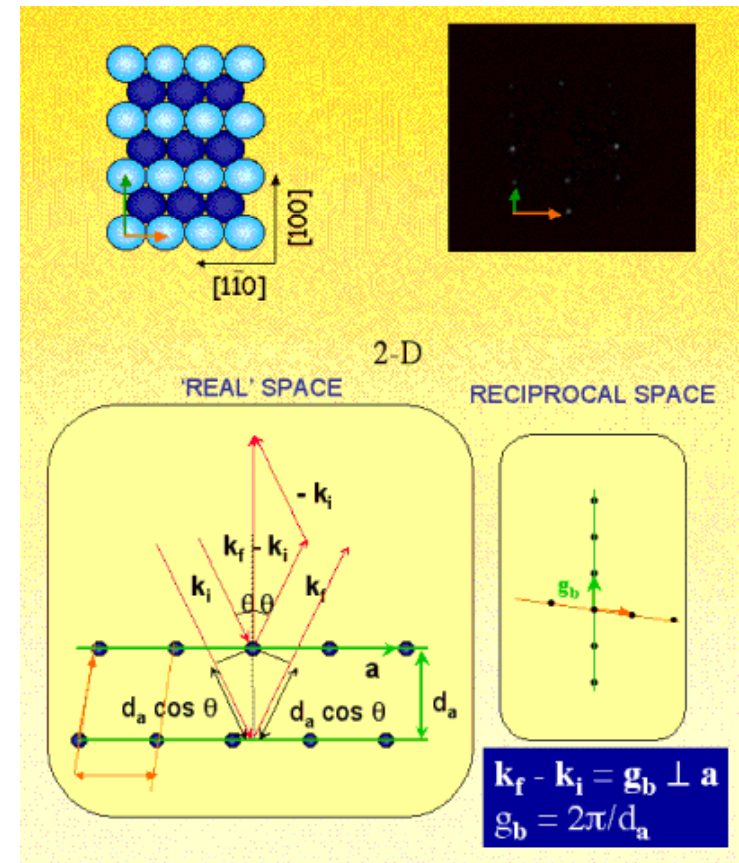
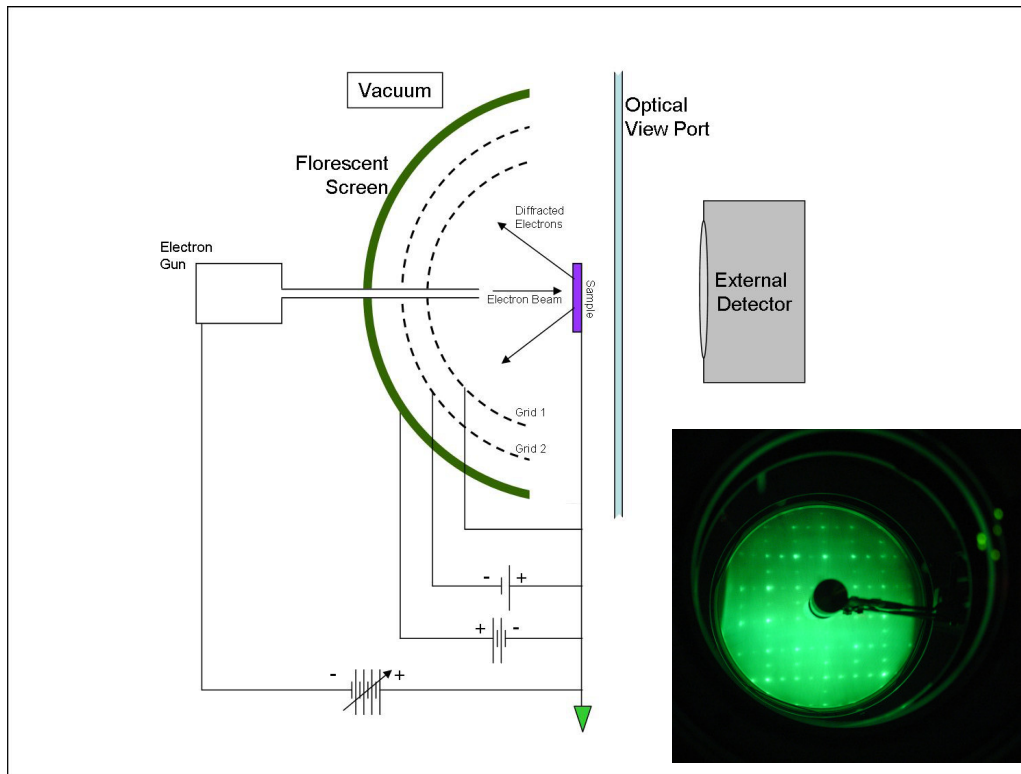


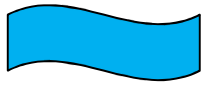
Warstwa epitaksjalna GaAs (wzrost 2D)  
w sąsiedztwie krystalitów GaAs (wzrost 3D)  
Wzrost - K. Pakuła (UW)



## Wykład 12

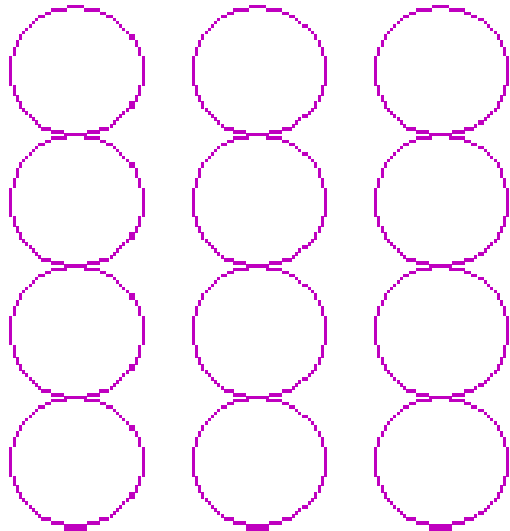
# Dyfrakcja nisko-energetycznych elektronów (LEED)



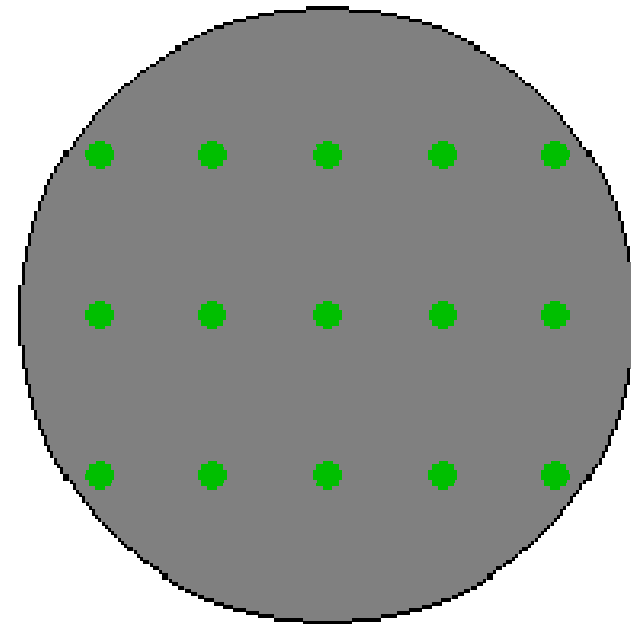


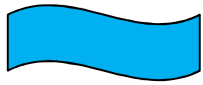
# Dyfrakcja nisko-energetycznych elektronów (LEED)

Real Space - fcc(110) surface



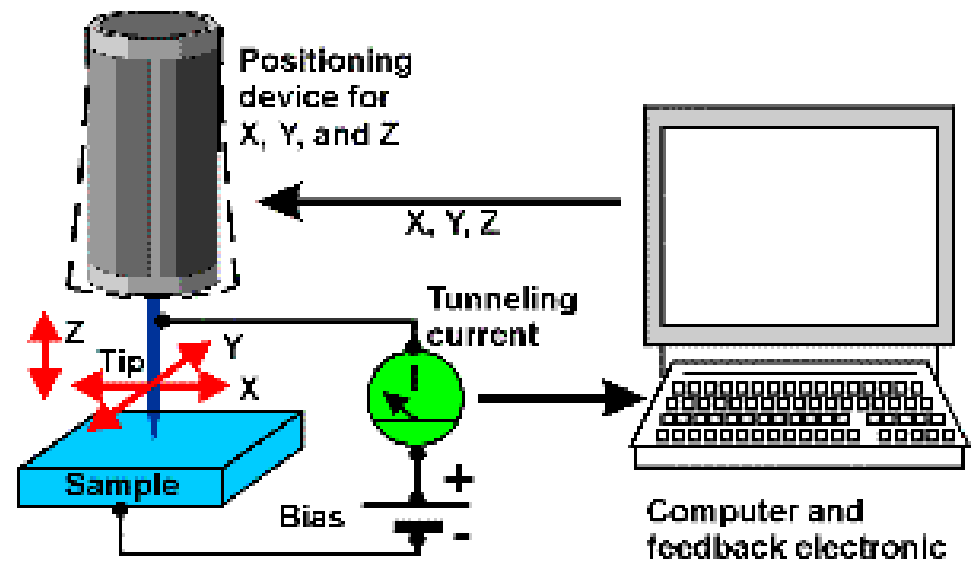
Diffraction Pattern



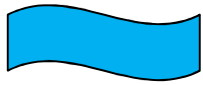


## Wykład 11

# Skaningowy Mikroskop Tunelowy (STM)







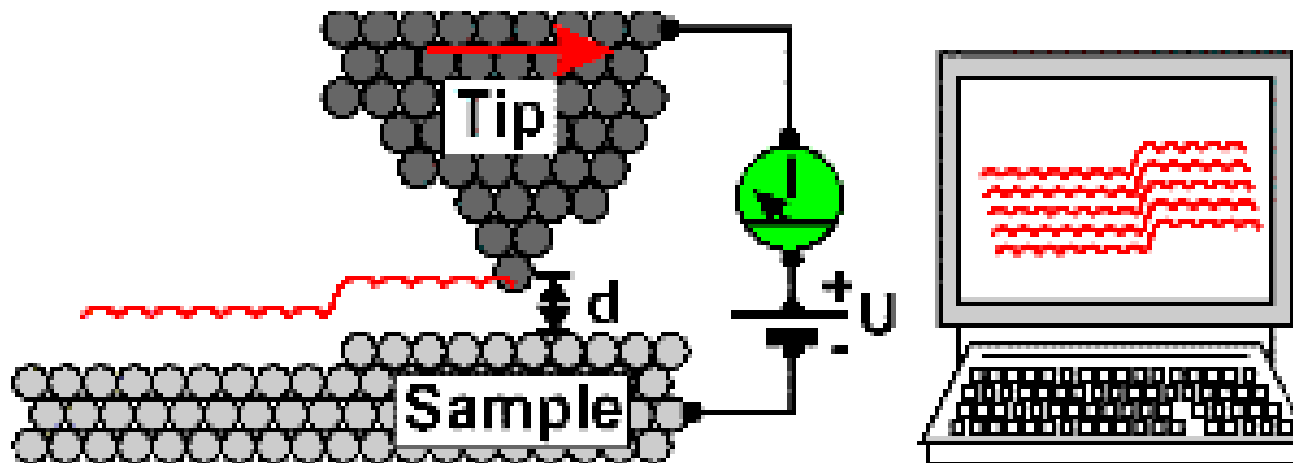
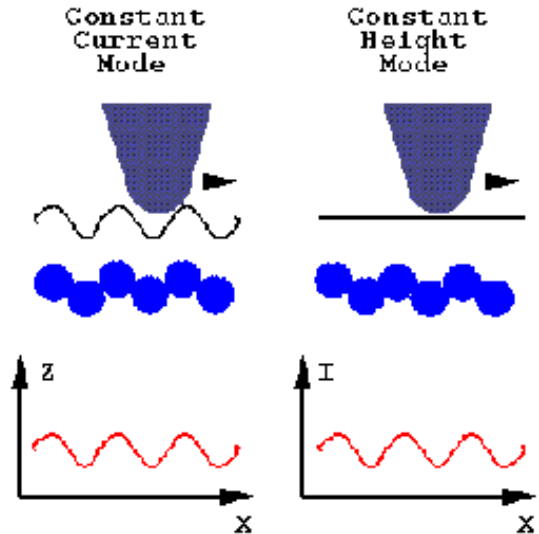
## Wykład 11

# Skaningowy Mikroskop Tunelowy (STM)

$$J_T \propto \left( \frac{V_T}{d} \right) \exp(-A\sqrt{\Phi}d)$$

$$A = 1.025 \text{ (eV)}^{-0.5} \text{ \AA}^{-1}$$

$\Phi$  – praca wyjścia





# The Nobel Prize in Physics 2010

Andre Geim, Konstantin Novoselov

## The Nobel Prize in Physics 2010

Andre Geim

Konstantin Novoselov



Photo: Sergeom, Wikimedia Commons

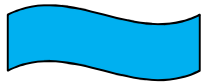
Andre Geim



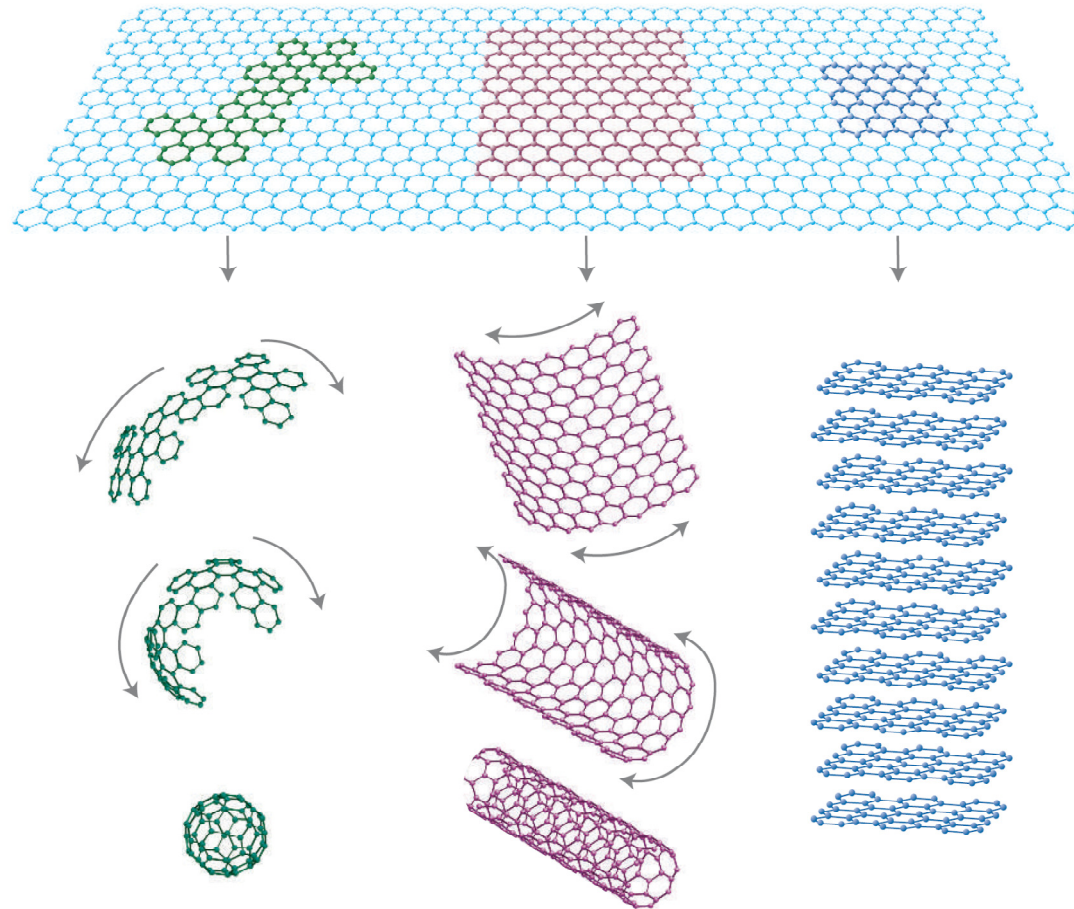
Photo: University of Manchester, UK

Konstantin Novoselov

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*



# Pojedyncza warstwa grafitu, grafen

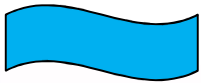


**fulereny**

**nanorurki**

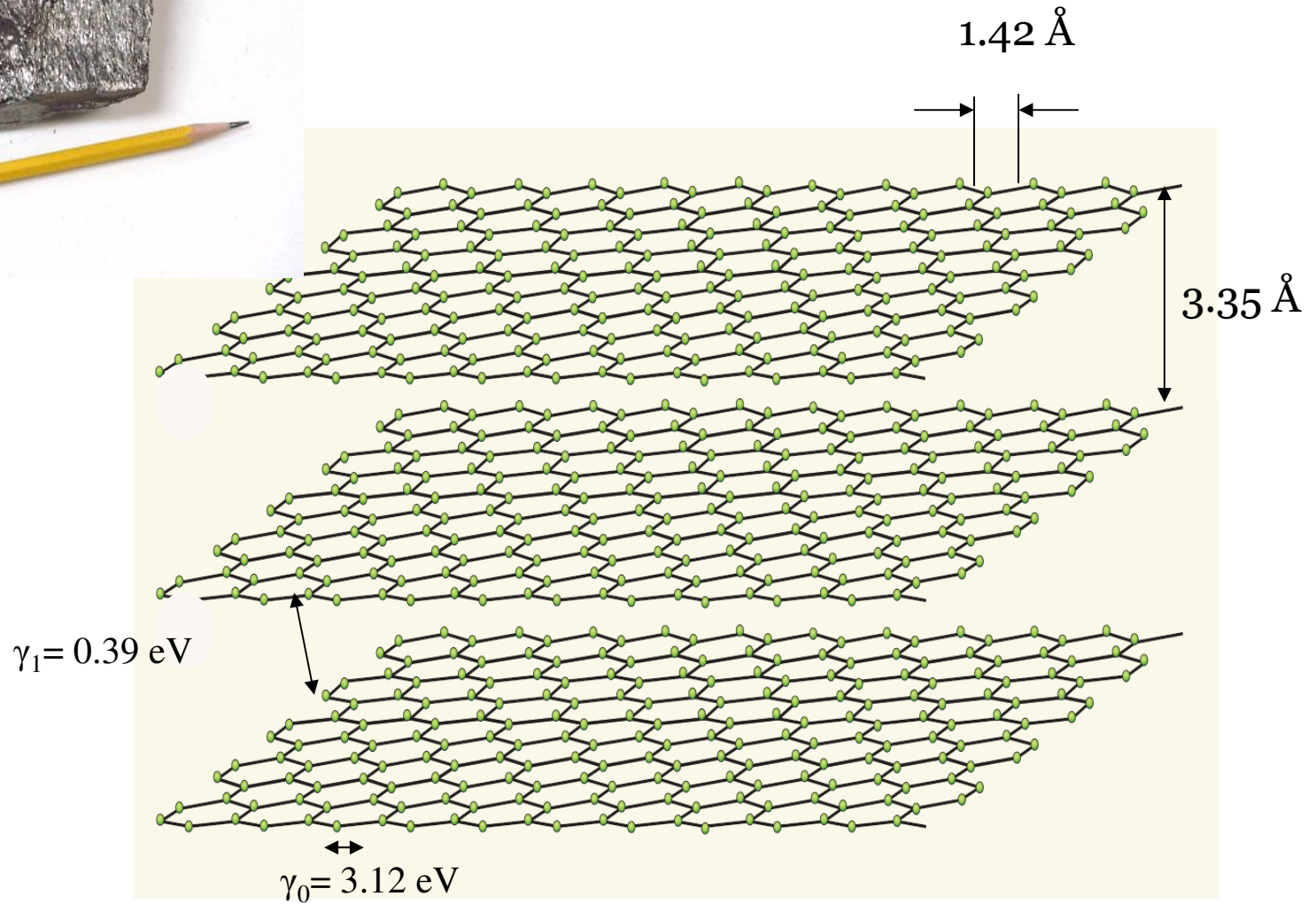
**grafit**

**Podstawowy budulec dla struktur węglowych....**

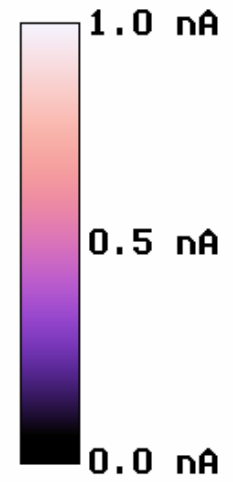
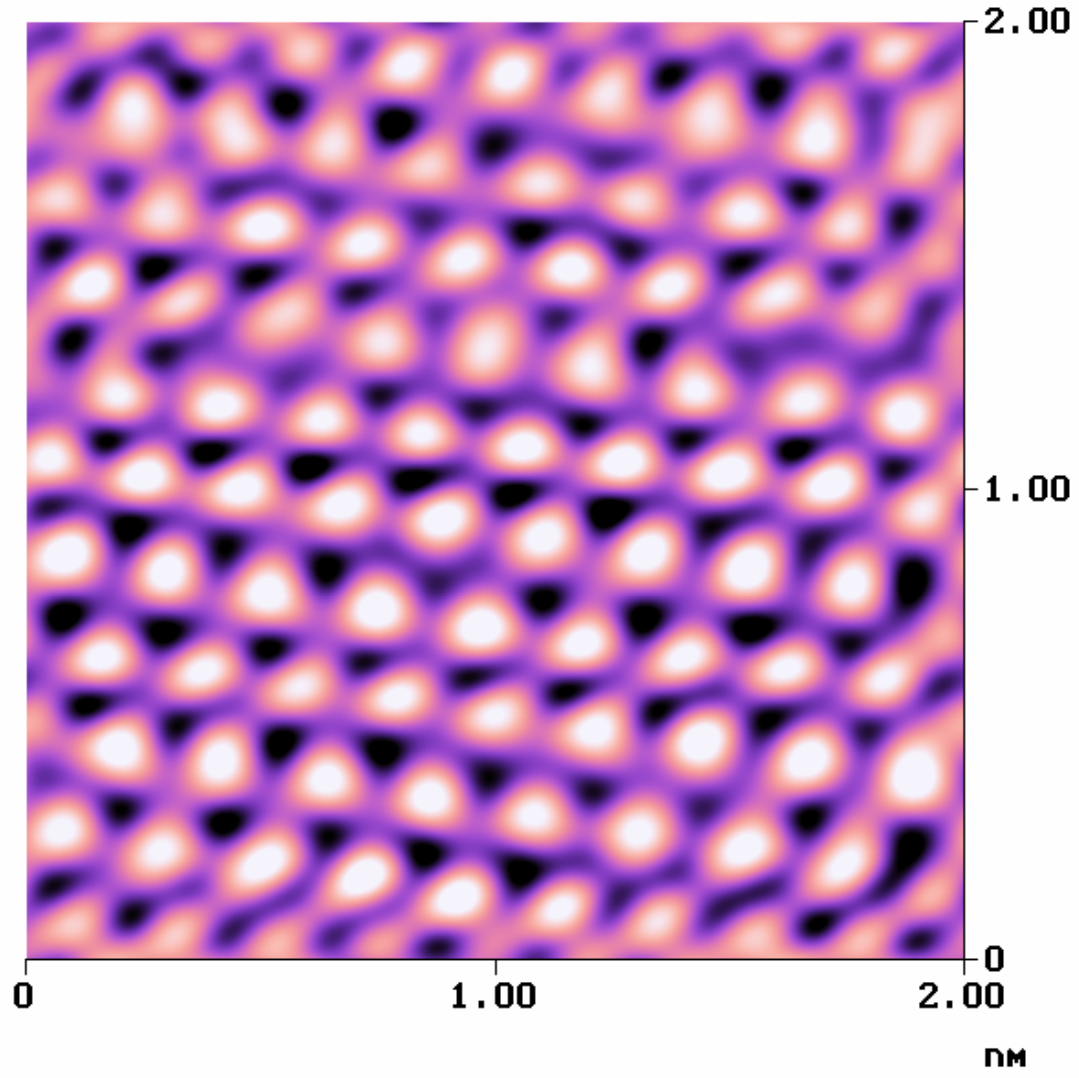


# Wykład 12

# Grafit



Height Angle Surface Normal Clear Calculator

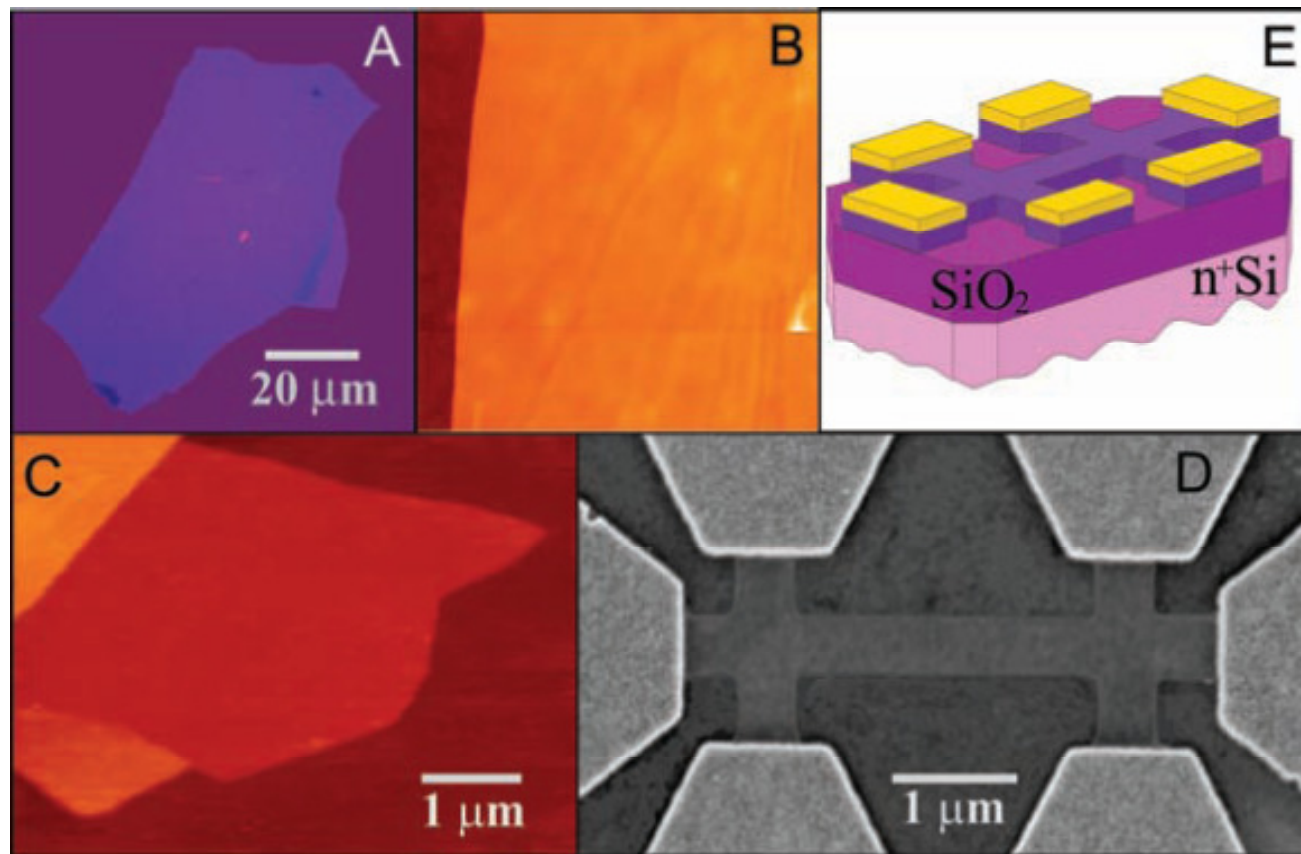


Digital Instruments NanoScope  
Scan size 2.000 nm  
Scan rate 54.93 Hz  
Number of samples 512  
Image Data Current  
Data scale 1.000 nA

grafit1.001

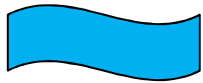
Height

# Metoda taśmy klejącej - badanie tego co zwykle łądowało w koszu...



**płatki z kilku warstw  
Rozmiary ~10 μm**

K. Novoselov, A. Geim *et al.* Science (2004)



## Wykład 12

# Komórka elementarna grafenu

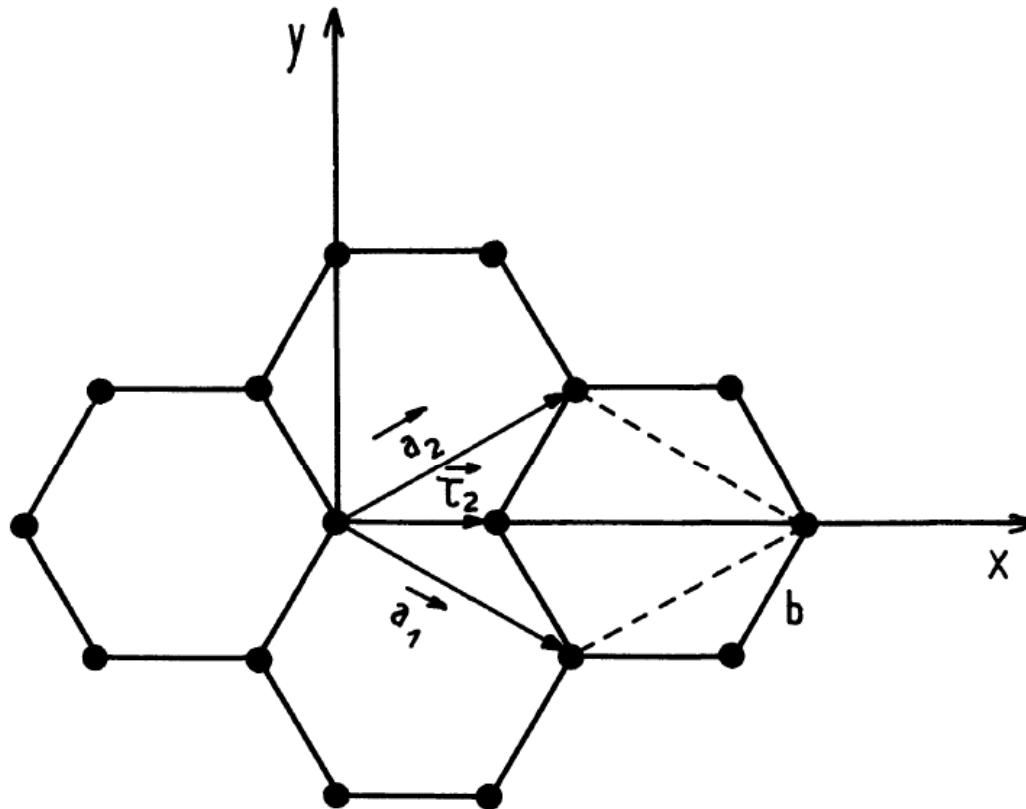
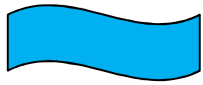


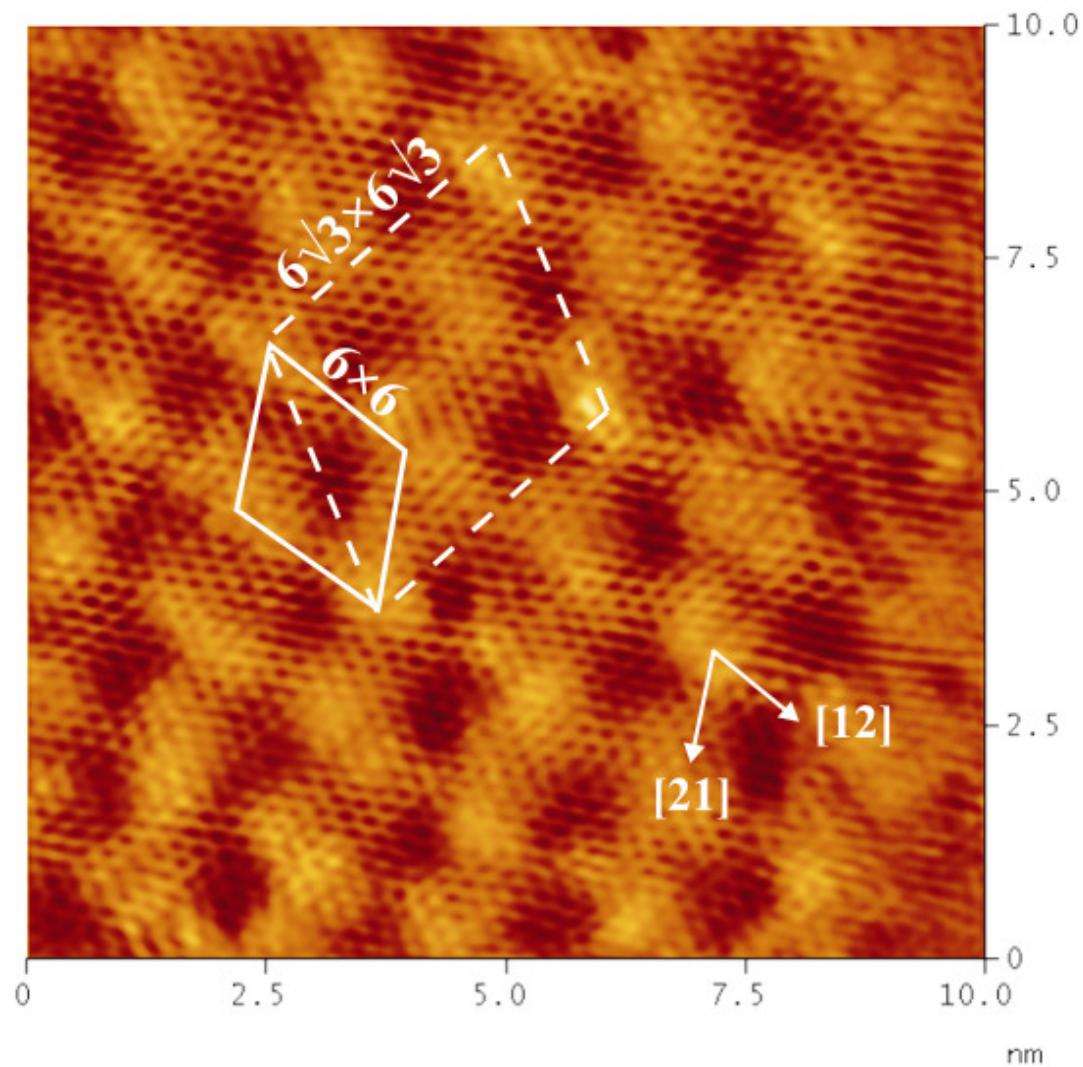
Fig. 1. — Unit cell of a single graphite layer.

*J. Blinowski et al., J. Physique 41 (1980) 47-58*



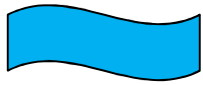
## Wykład 12

# Mikroskop tunelowy (STM)



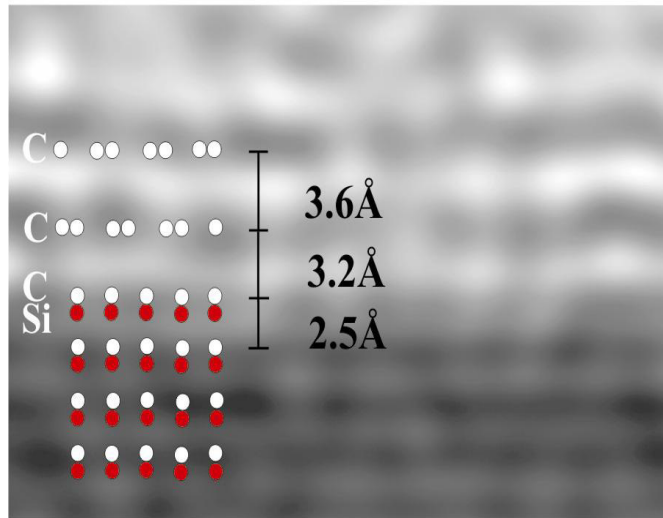
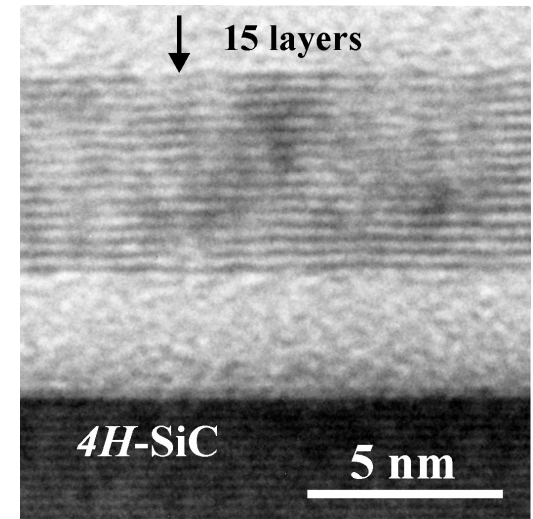
Grafen na podłożu 4H-SiC(0001), strona Si (R.Bożek)



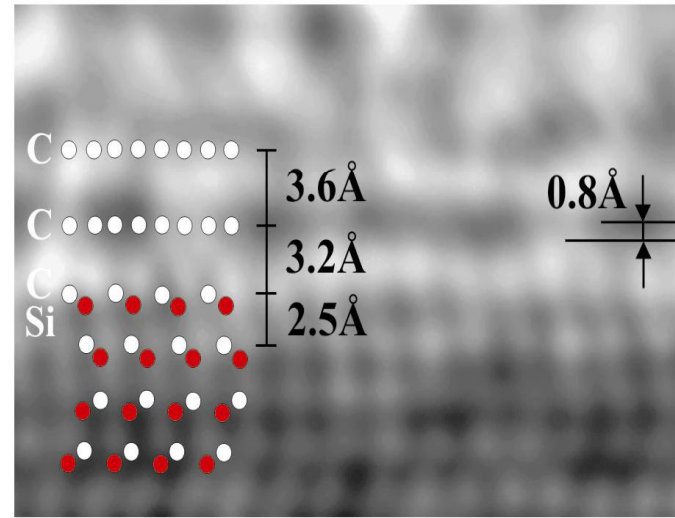


# Wykład 12

Grafen - Elektronowy mikroskop transmisyjny  
HRTEM (wysoka rozdzielczość)



[1100] sample orientation



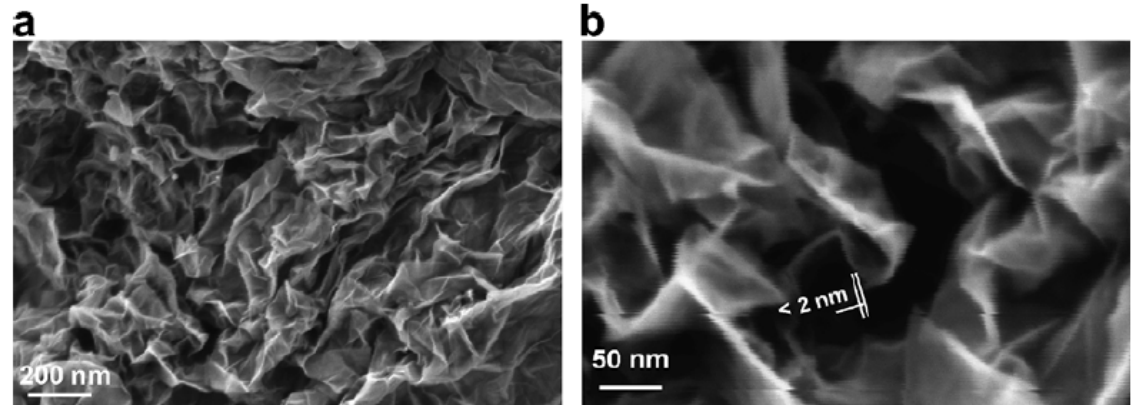
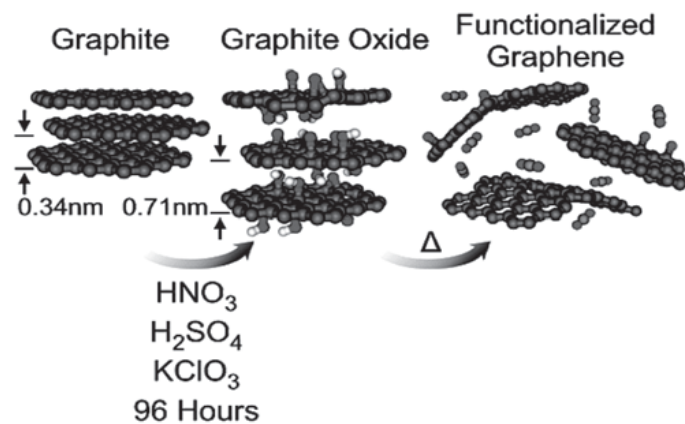
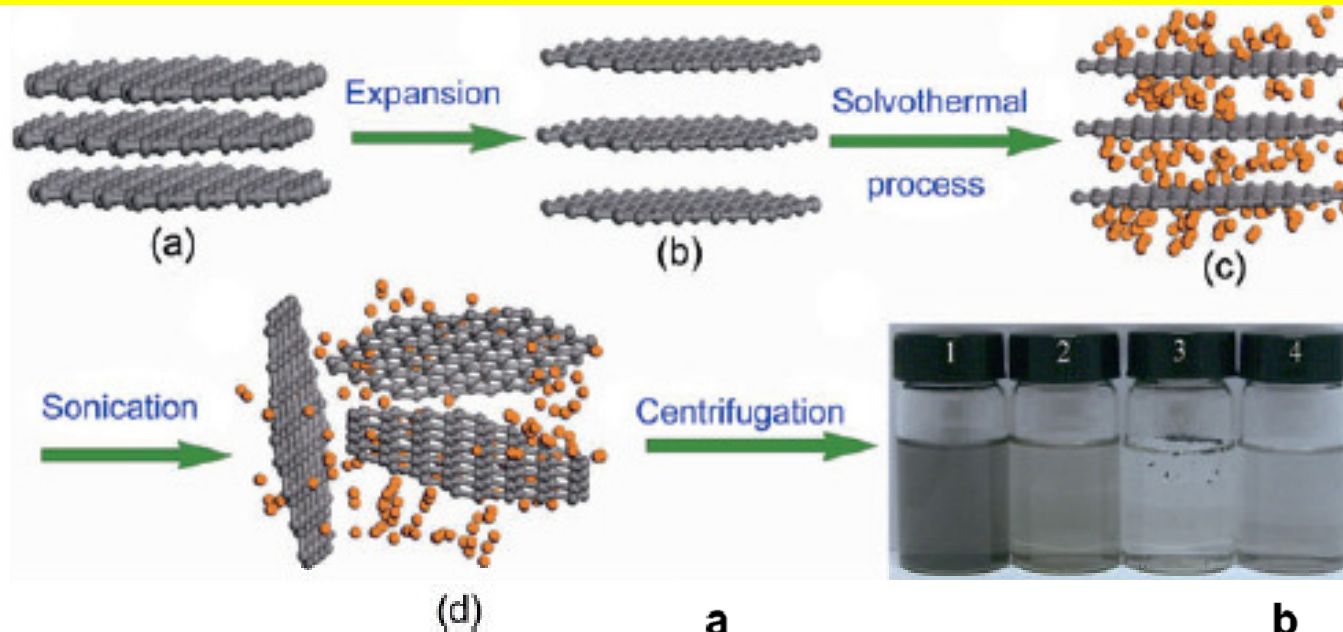
[1120]

HRTEM J. Borysiuk

Pierwsza warstwa na stronie C jest oddalona od SiC przeszło 3Å.  
Oznacza to mniejsze oddziaływanie z SiC...

Inne metody wytwarzania grafenu...

# Rozwarstwianie grafitu...



S. Stankovich et al., Carbon **45** 1558(2007)

Y. Hernandez et al., Nature nanotechnology **3**, 563 (2008)

W. Quian et al., Nano Res **2**, 706 (2009)

A. Ciesielski and P. Samori, Chem. Soc. Rev. **43**, 381 (2014)

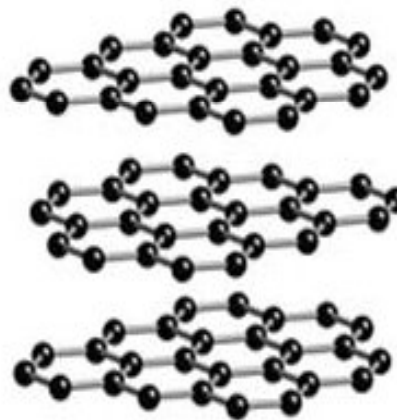
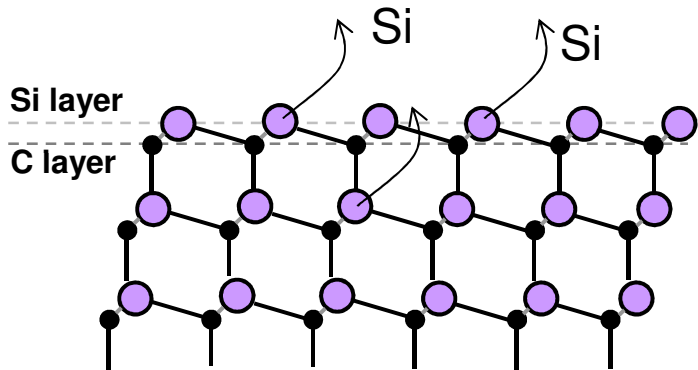
# Obiecująca metoda otrzymywania grafenu...

Wgrzewanie SiC

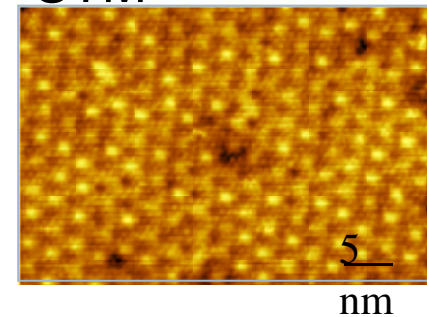
T (>1400°C); wysoka próżnia

SiC

Kilka, kilkadziesiąt warstw węglowych



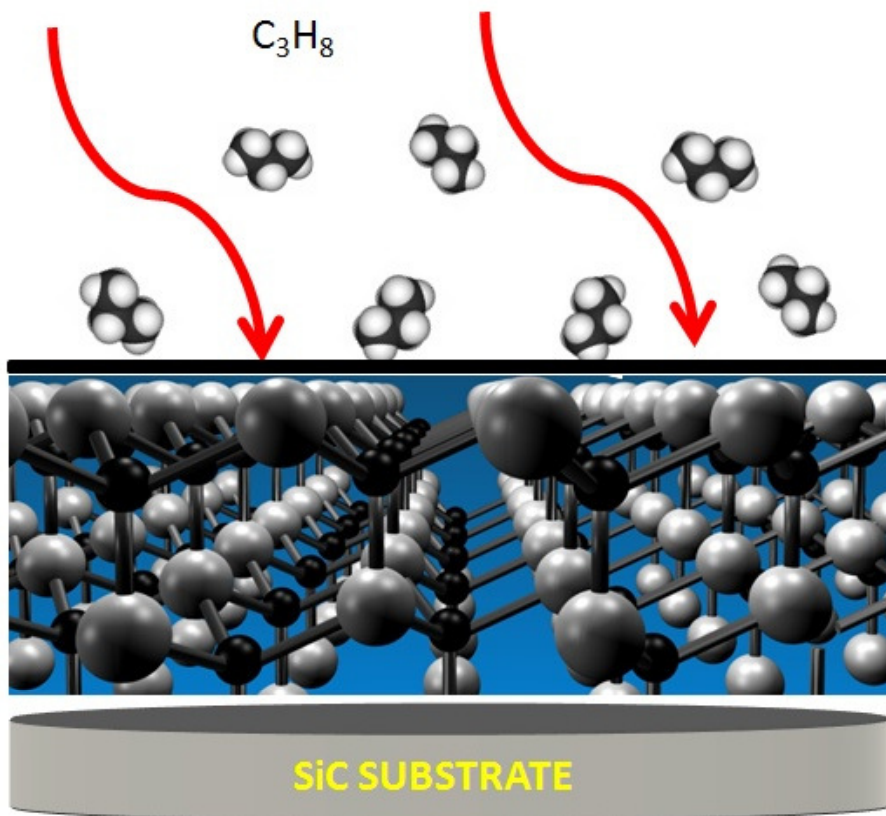
STM



van Bommel *et al.*, Surface Science 1975  
Oshima *et al.*, J. Phys. Cond. Matt. 1997  
Forbeaux *et al.*, PRB 1998  
**Berger *et al.*, J. Phys. Chem. 2004, Science 2006**



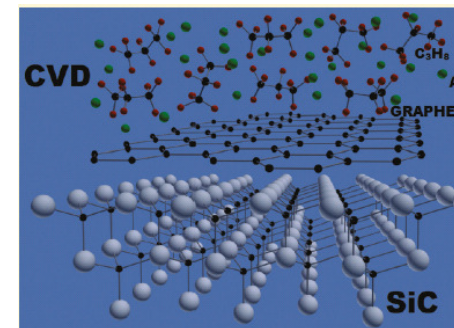
2006/2007



Nowy pomysł:  
„prawdziwa epitaksja”  
(osadzanie)

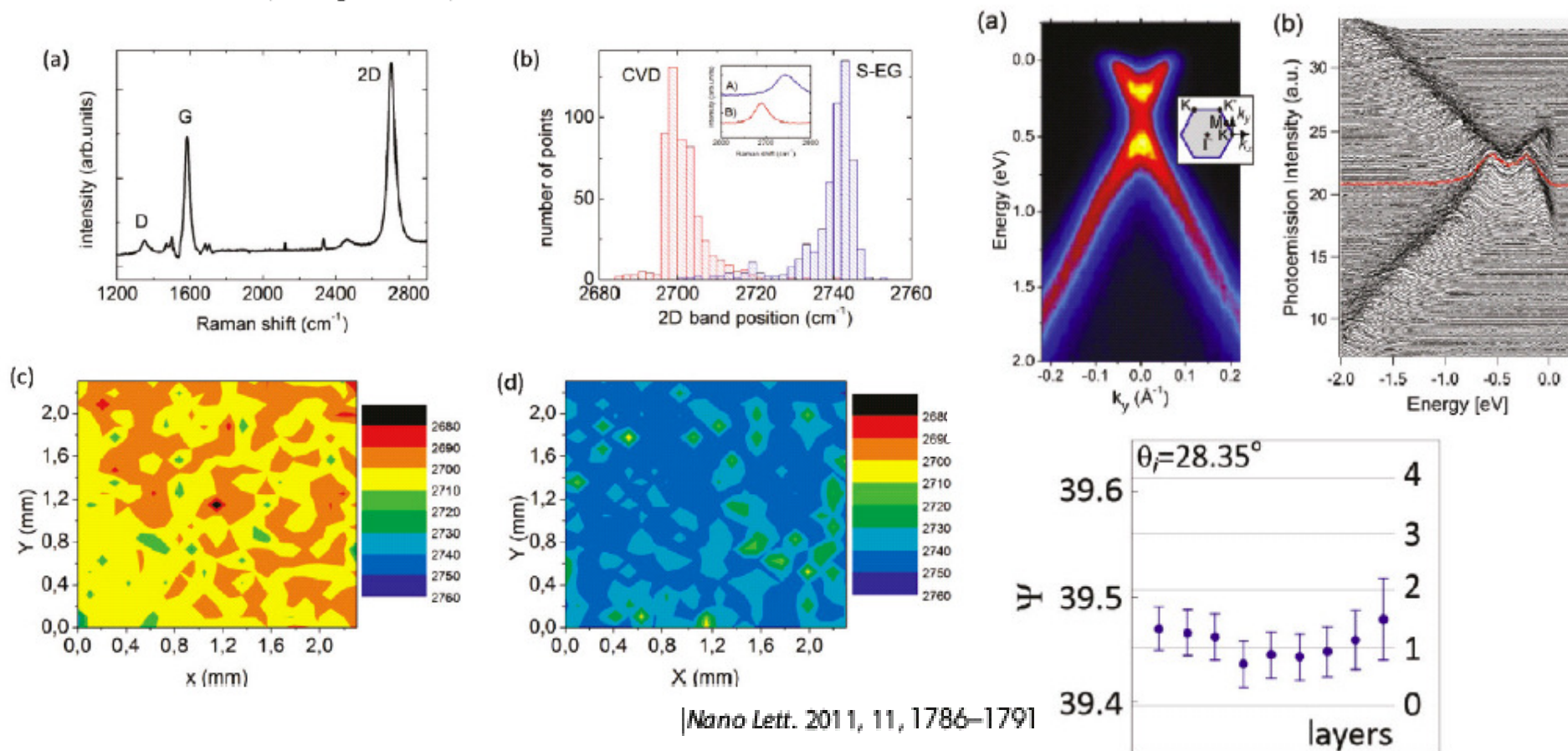
### Zalety

- kontrola transportu masy
- mniejsze naprężenia warstw
- mniejsza wrażliwość na stopnie na podłożach
- lepsza kontrola grubości
- kompatybilność z technologią SiC

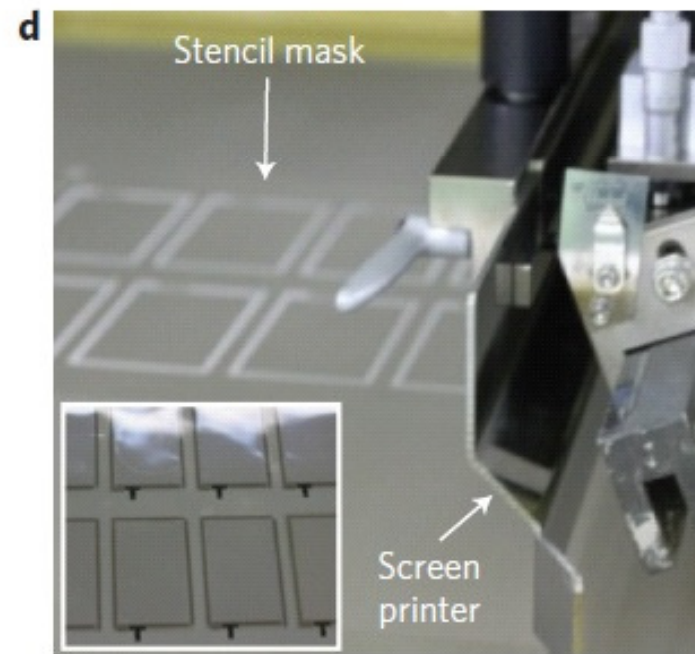
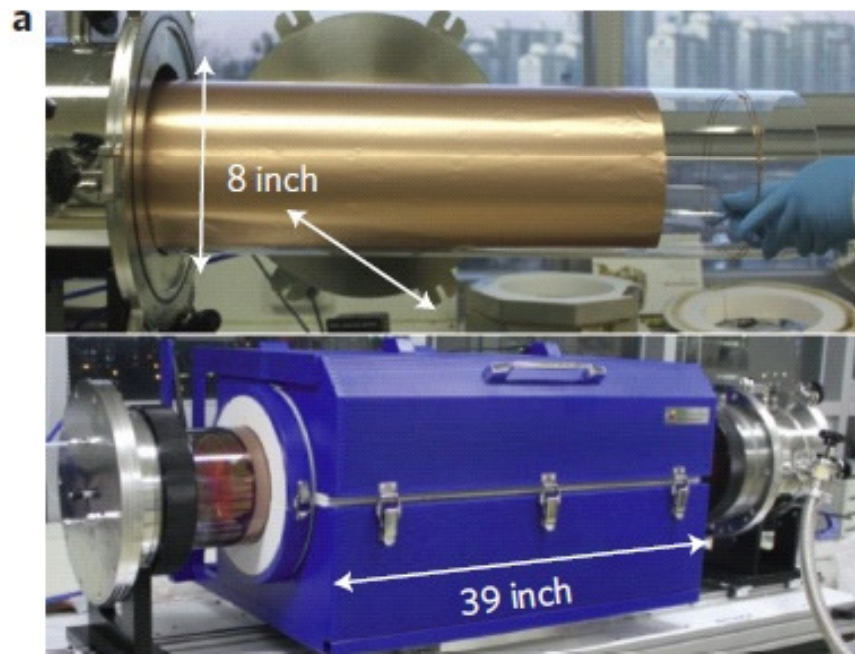
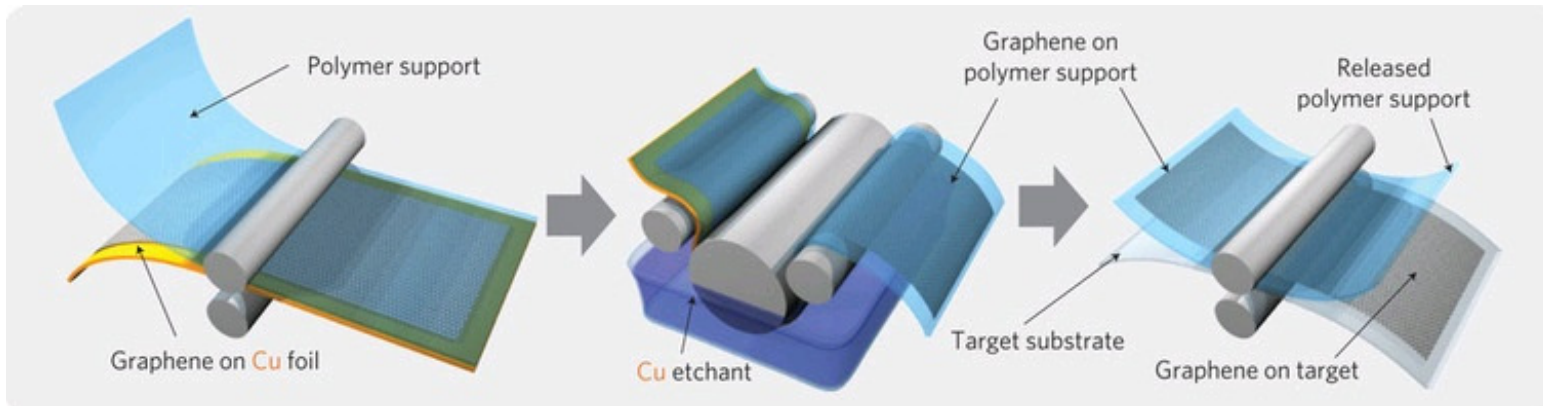


## Graphene Epitaxy by Chemical Vapor Deposition on SiC

W. Strupinski,<sup>\*1</sup> K. Grodecki,<sup>1,2</sup> A. Wyszomlek,<sup>2</sup> R. Stepniewski,<sup>2</sup> T. Szkopek,<sup>3</sup> P. E. Gaskell,<sup>3</sup> A. Grüneis,<sup>4,5</sup> D. Haberer,<sup>4</sup> R. Bozek,<sup>2</sup> J. Krupka,<sup>6</sup> and J. M. Baranowski<sup>1,2</sup>

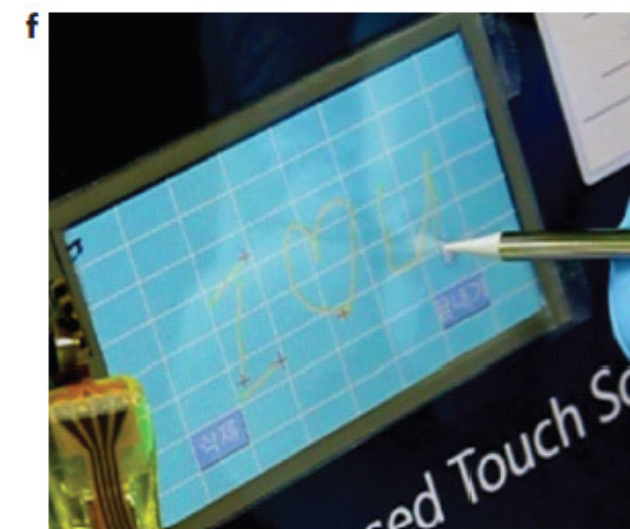
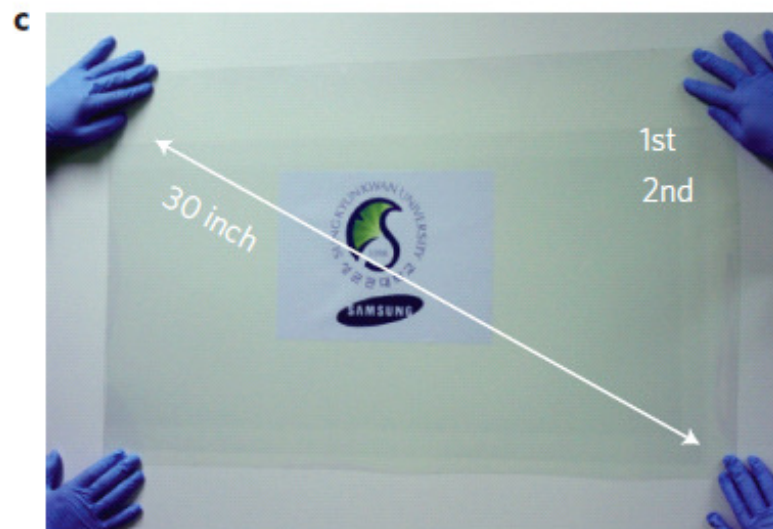
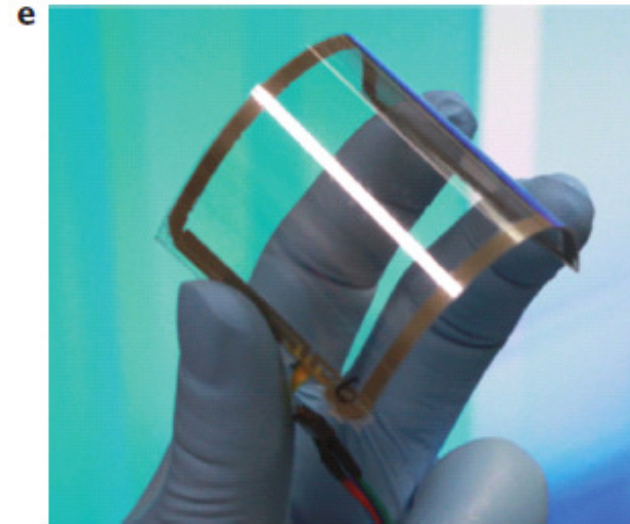
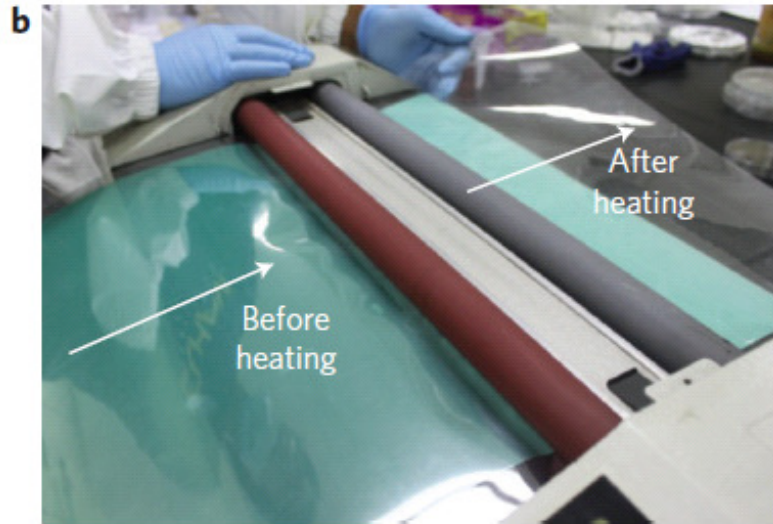


# Grafen „roll-to-roll”



Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)

**NATURE NANOTECHNOLOGY**



Bae et al. NATURE NANOTECHNOLOGY 5,574 (2010)



# Produkcja grafenu w Polsce

## Manufacturing capacities



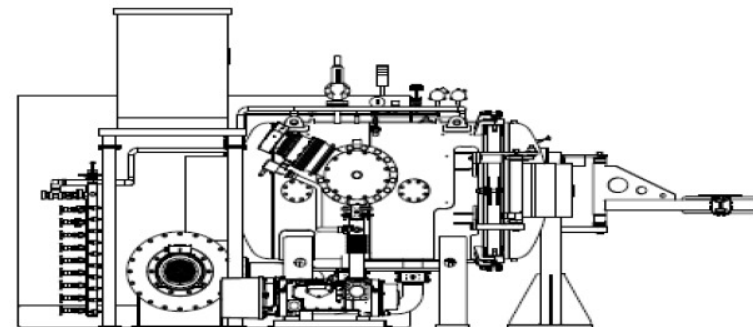
Small dimensions substrates



Wafers & foils < 6''



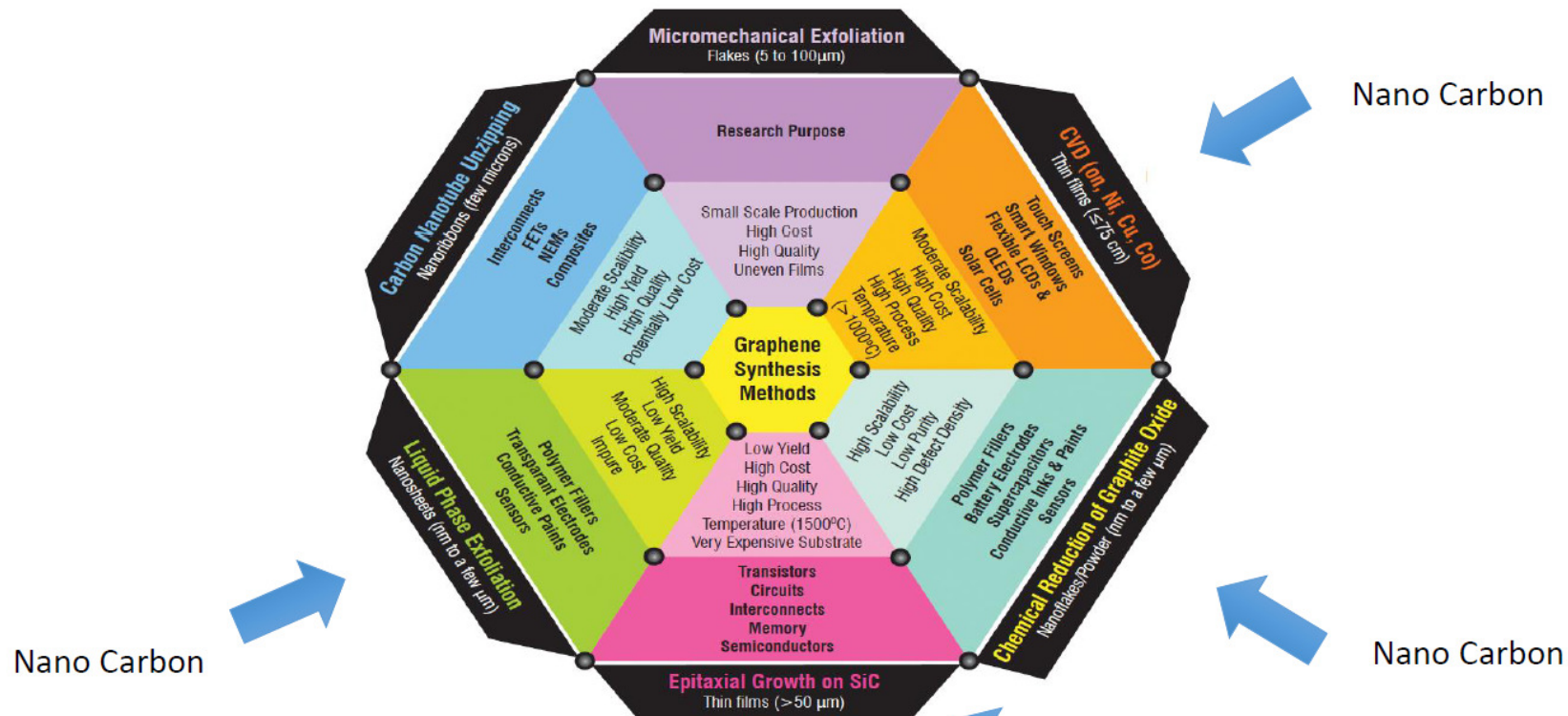
**CVD** 300mm x 300mm Cu foil  
May 2014



**CVD** 500mm x 500mm Cu foil  
installation 2014

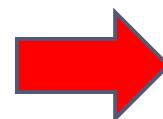
Źródło: ARP

# Positioning of Nano-Carbon



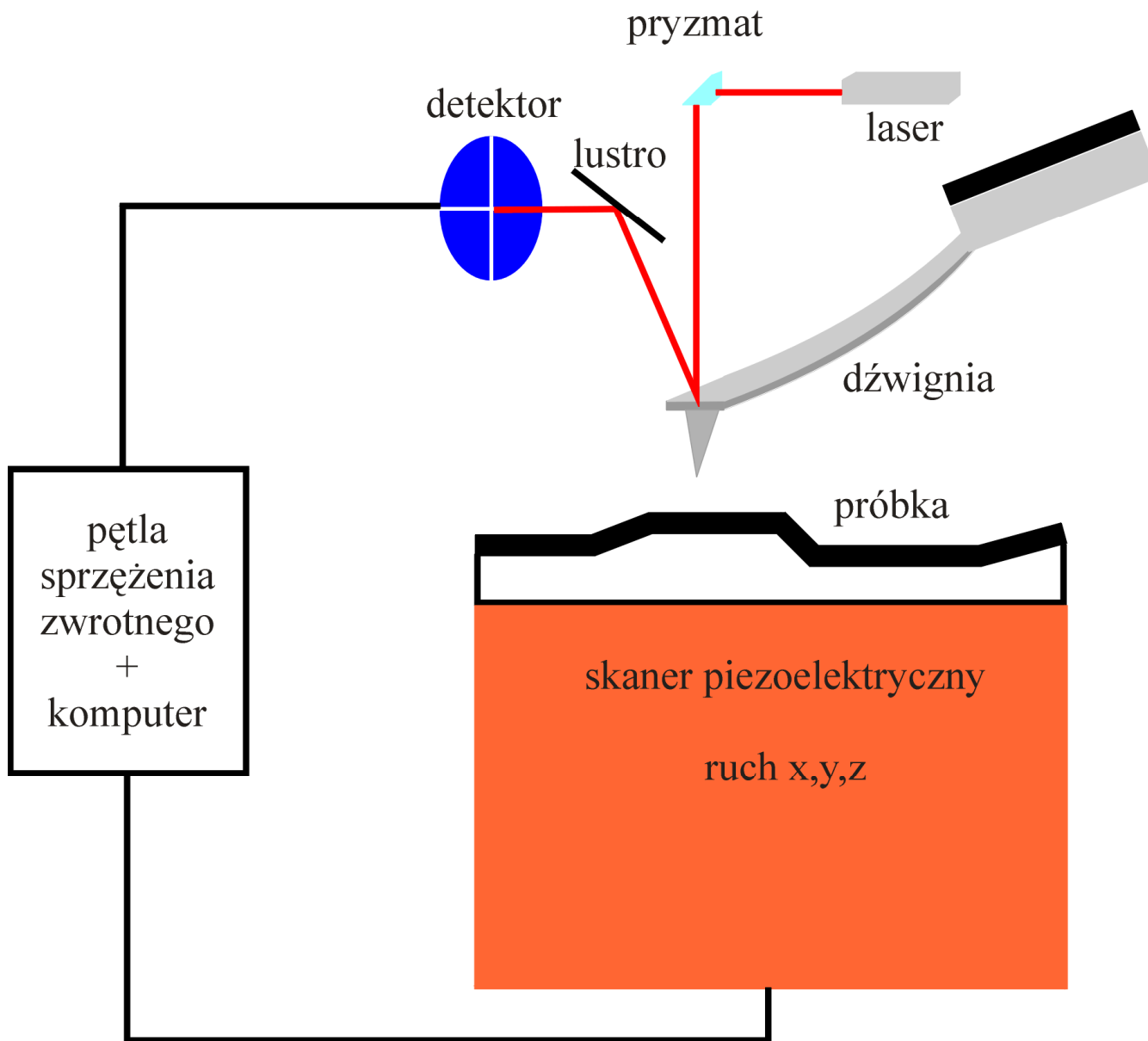
[www.nano-carbon.pl](http://www.nano-carbon.pl) [www.grapheneshop.pl](http://www.grapheneshop.pl)

Sprawdźmy co można kupić!



<http://www.grapheneshop.pl/>

# ZASADA DZIAŁANIA MIKROSKOPU SIŁ ATOMOWYCH

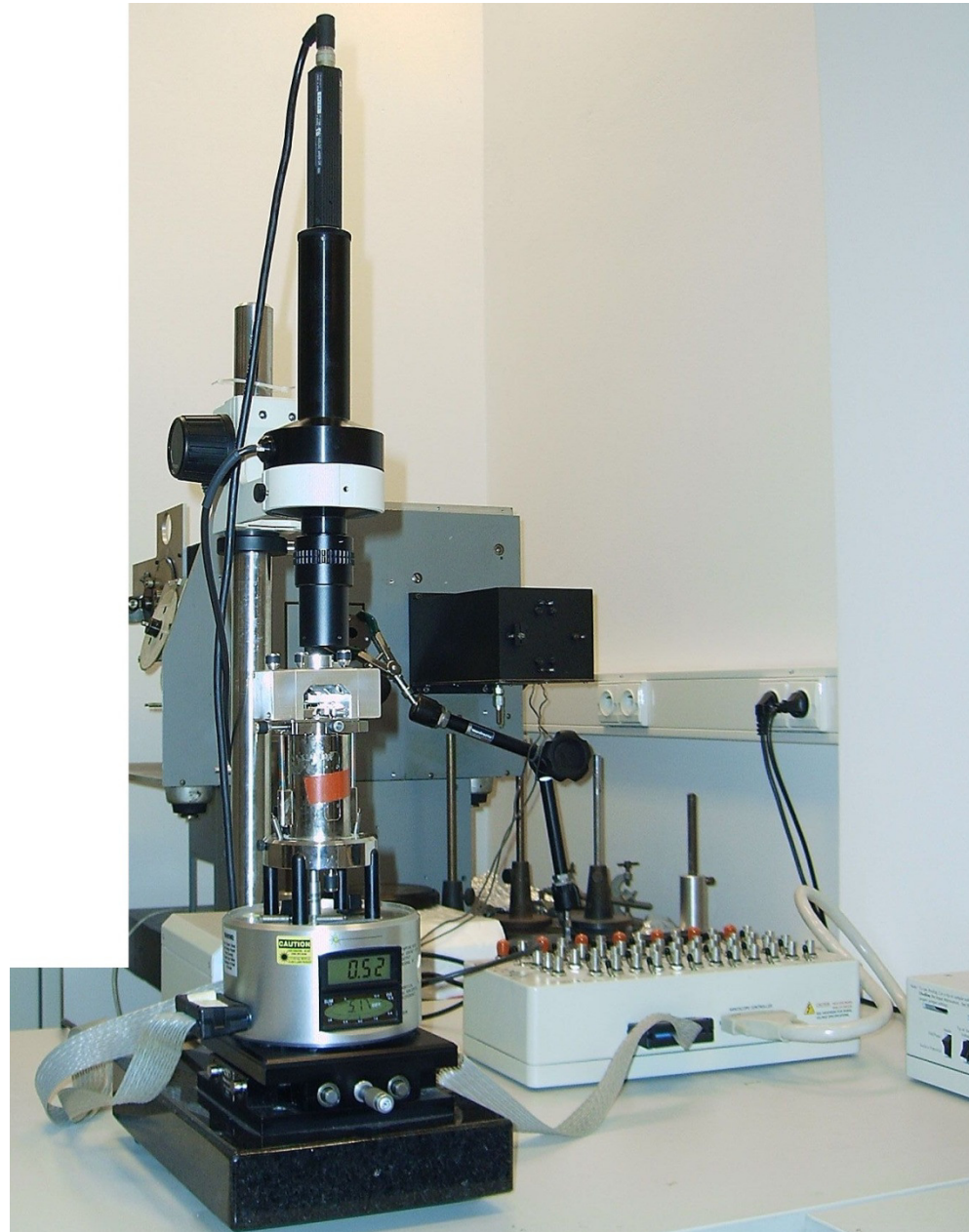


# Mikroskop AFM

mikroskop  
optyczny  
z kamerą

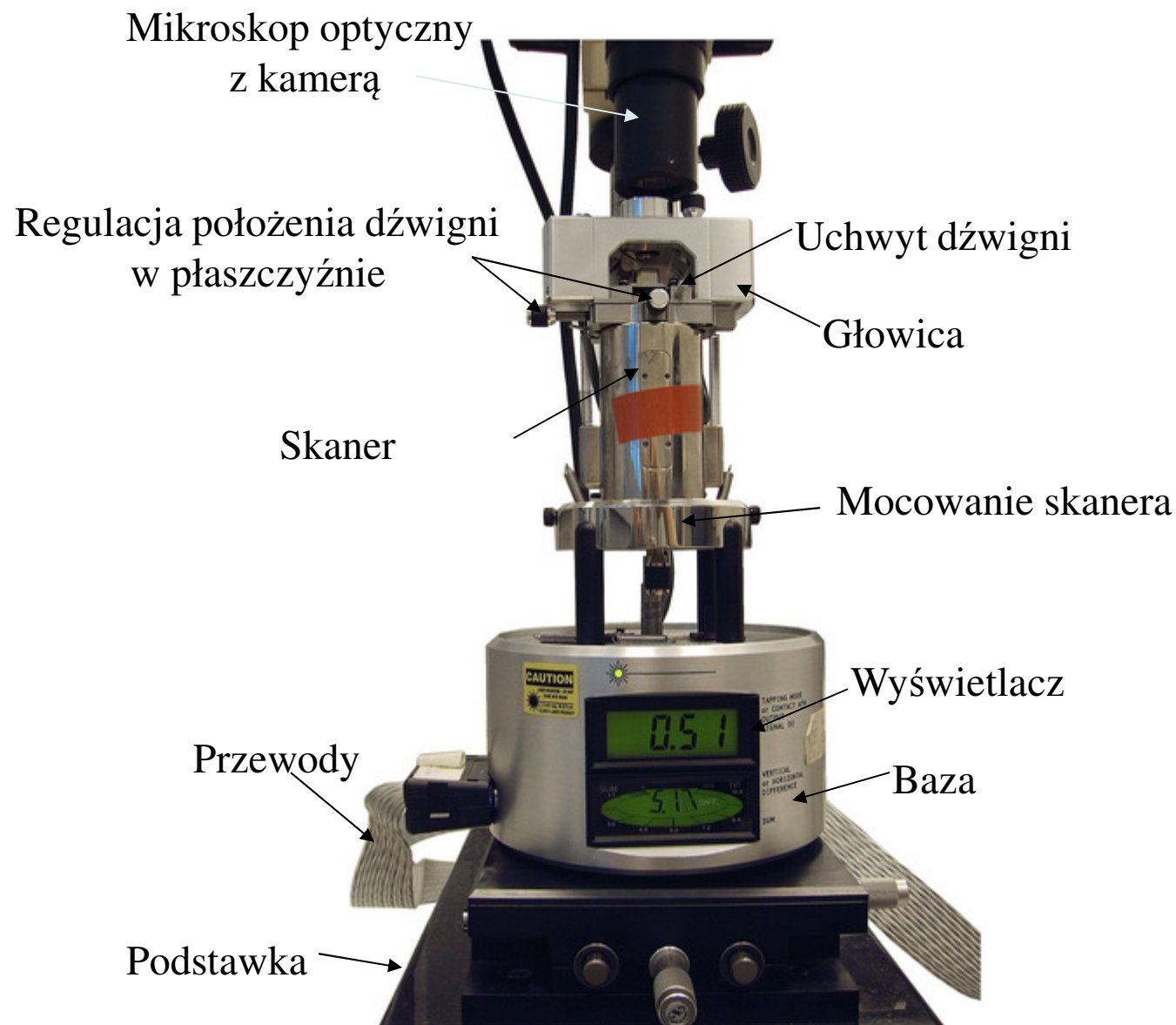
AFM  
~25cm

podstawa

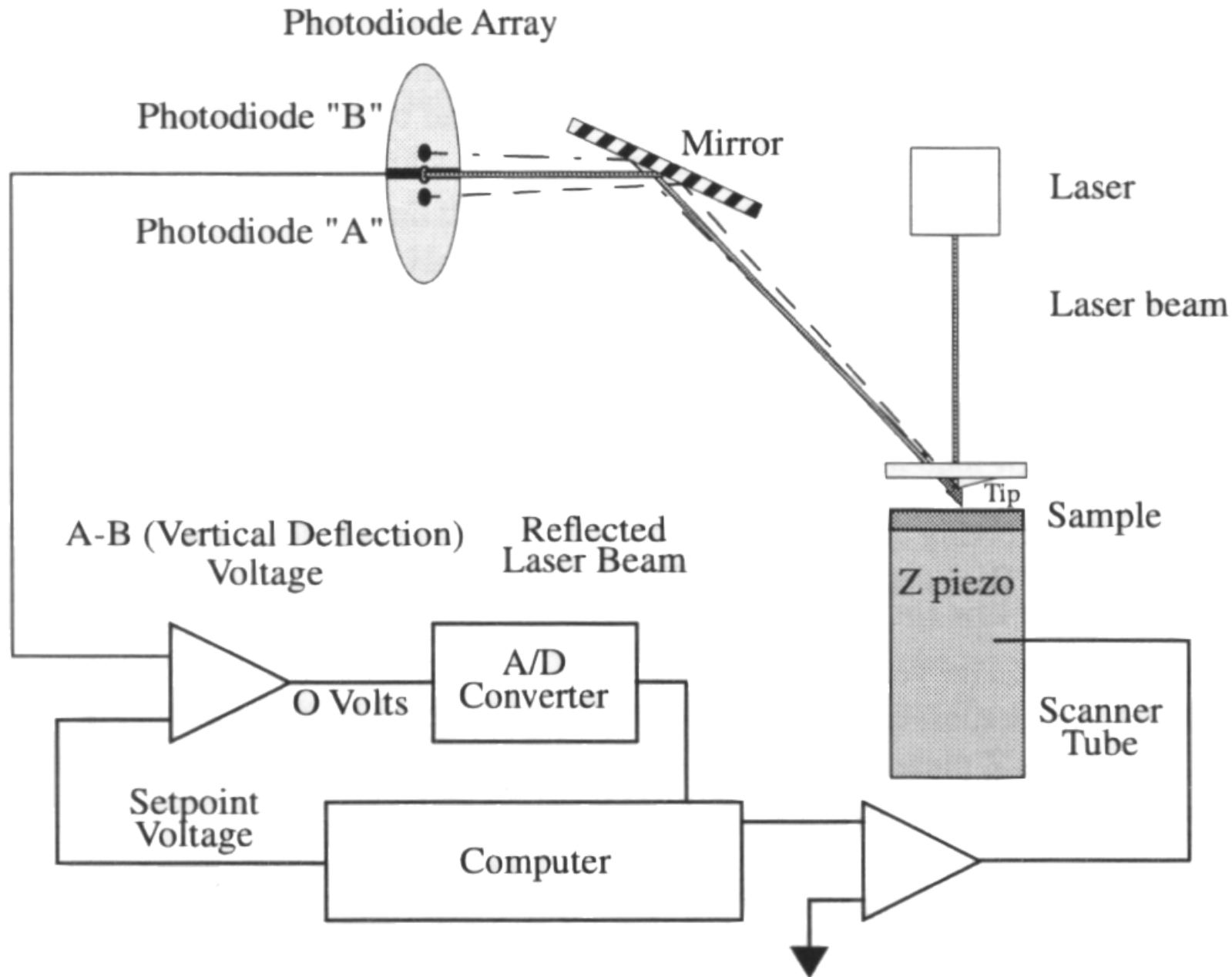


MultiMode AFM  
+Nanoscope IIIa  
Digital Instruments  
(obecnie Veeco)

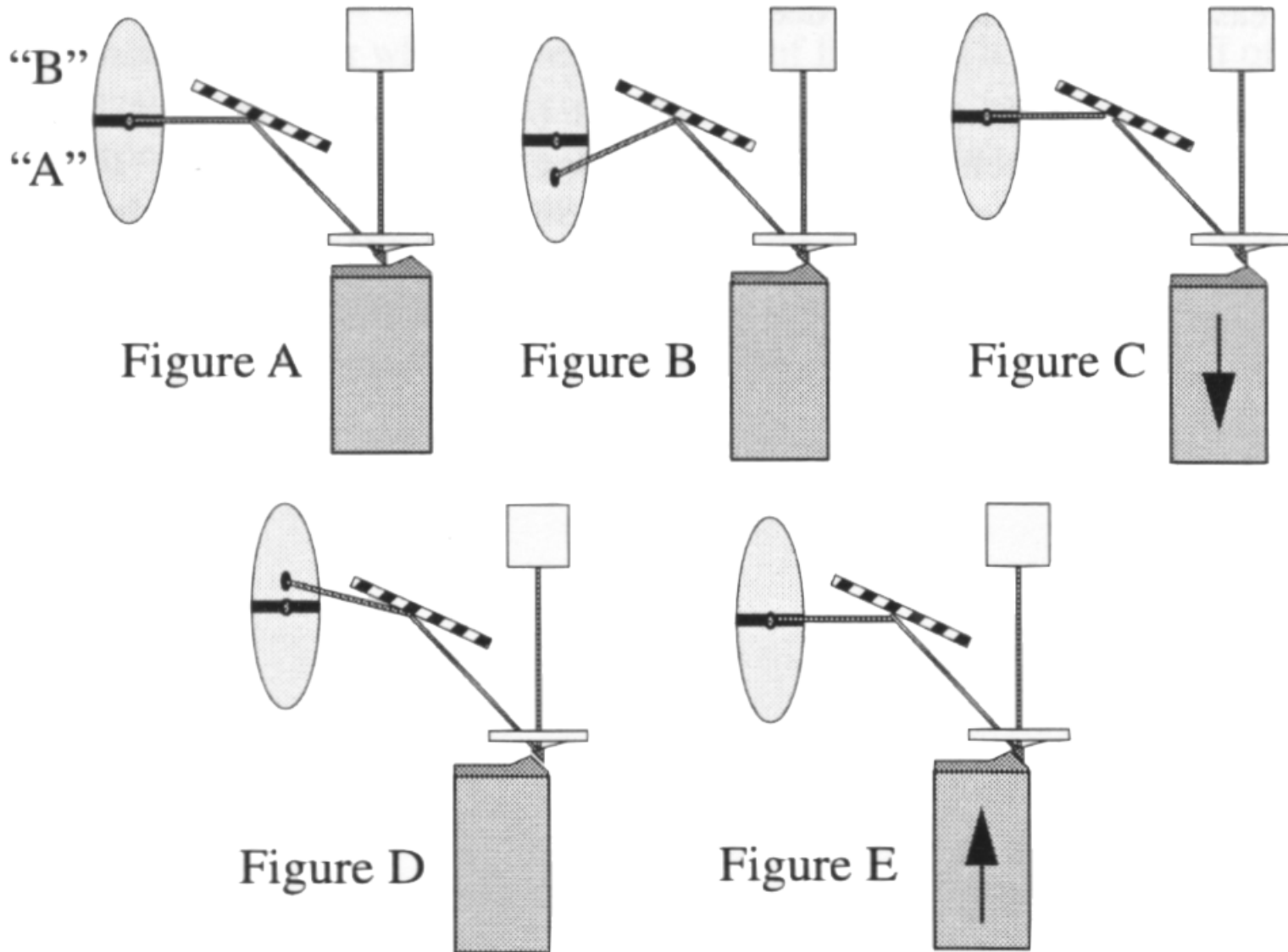
# Budowa mikroskopu AFM: ruchoma próbka



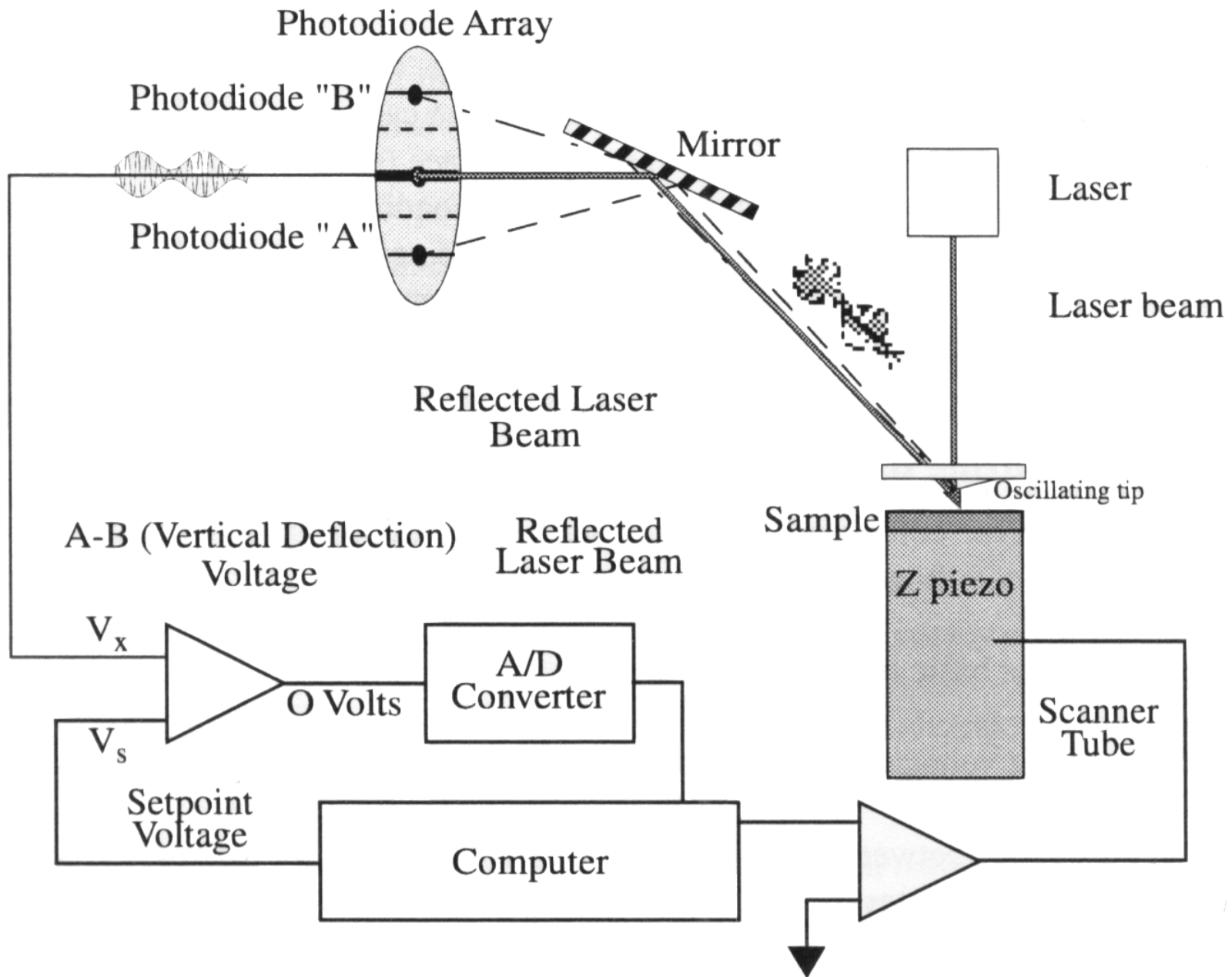
# Tryb kontaktowy („contact mode”)



# Tryb kontaktowy („contact mode”)

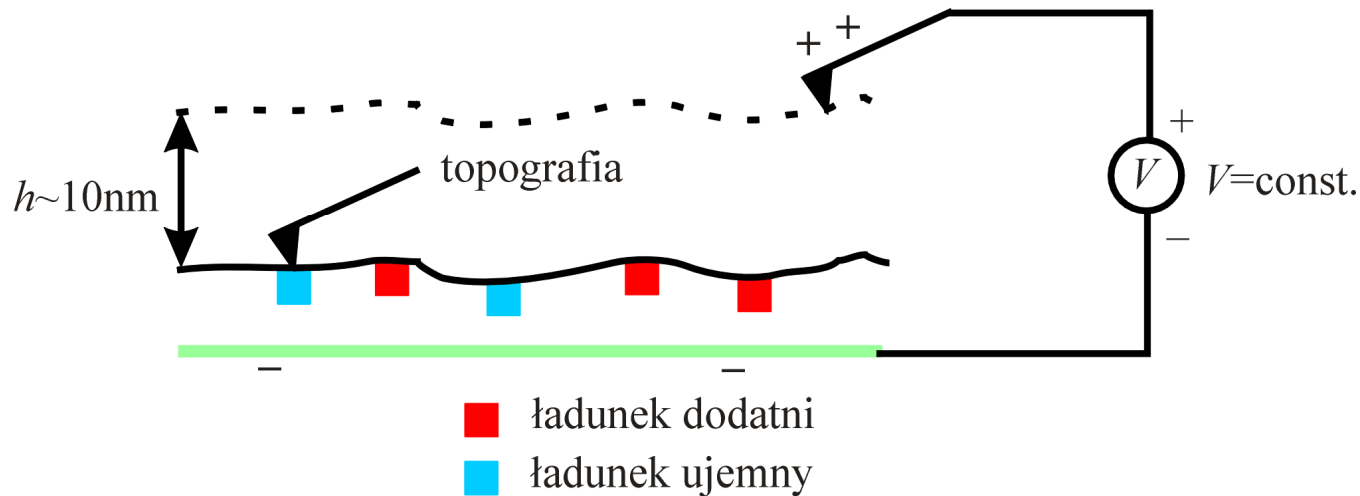


# (TappingMode™ AFM)





# EFM – Electric Force Microscopy (Kelvin Probe Microscopy)

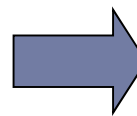


$$F(x) = F(x_0) + (x - x_0) \frac{\partial F}{\partial x} + \dots \quad \Delta\omega_0 = \frac{1}{2} \frac{\partial F}{\partial x} \frac{\omega_0}{k}$$

Siła elektryczna (gradient)  $\Leftrightarrow$  zmiana częstotliwości rezonansowej

Pętla sprzężenia zwrotnego: utrzymanie rezonansu

**Przyciąganie  $\Leftrightarrow$  Spadek częstotliwości**  
**Odpychanie  $\Leftrightarrow$  Wzrost częstotliwości**

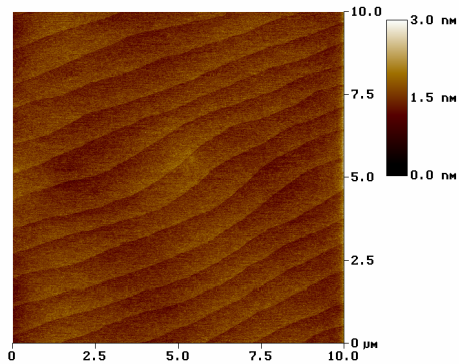


Doświadczenie w skali makro  
z ciężarkiem na brzeszczocie  
i magnesami...

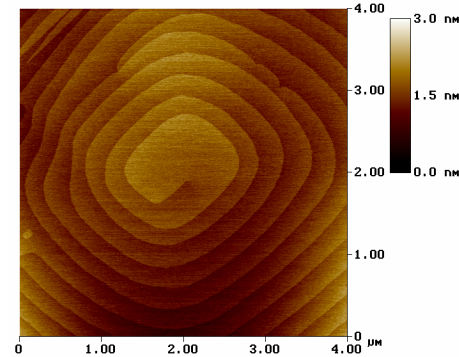


## Wykład 12

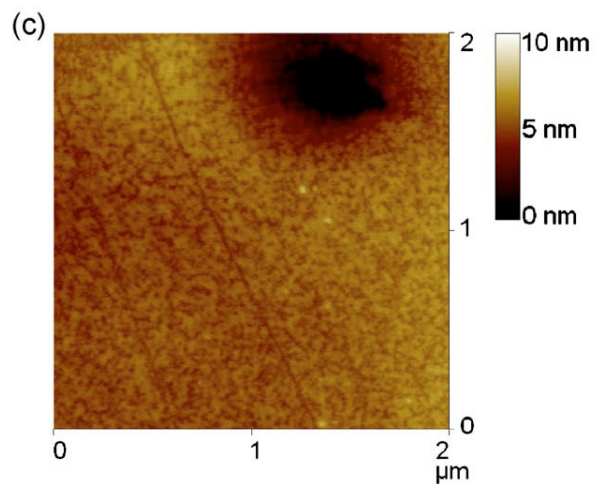
# Mikroskop sił atomowych (AFM)



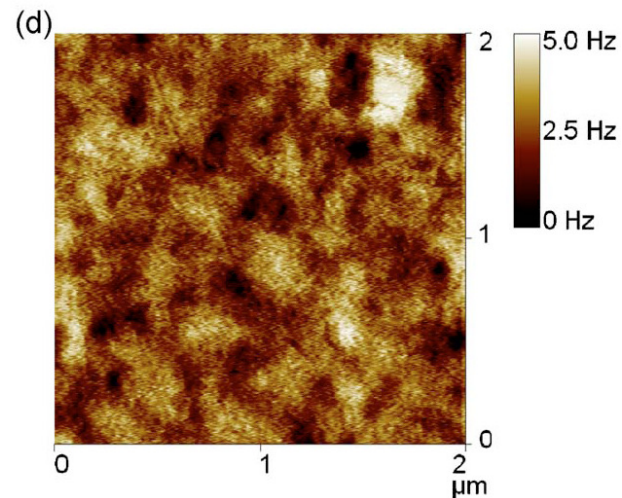
GaAs



Dyslokacja w InSb



AFM

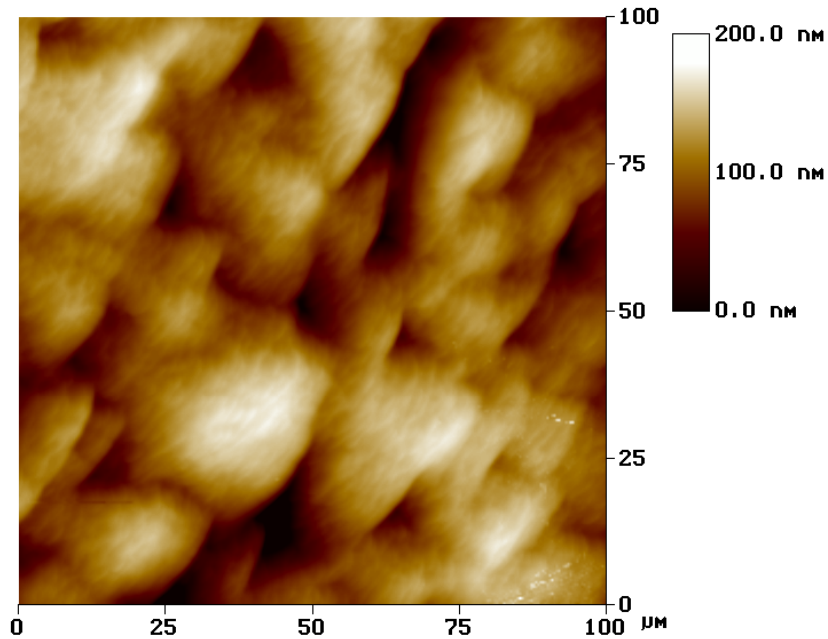


MFM

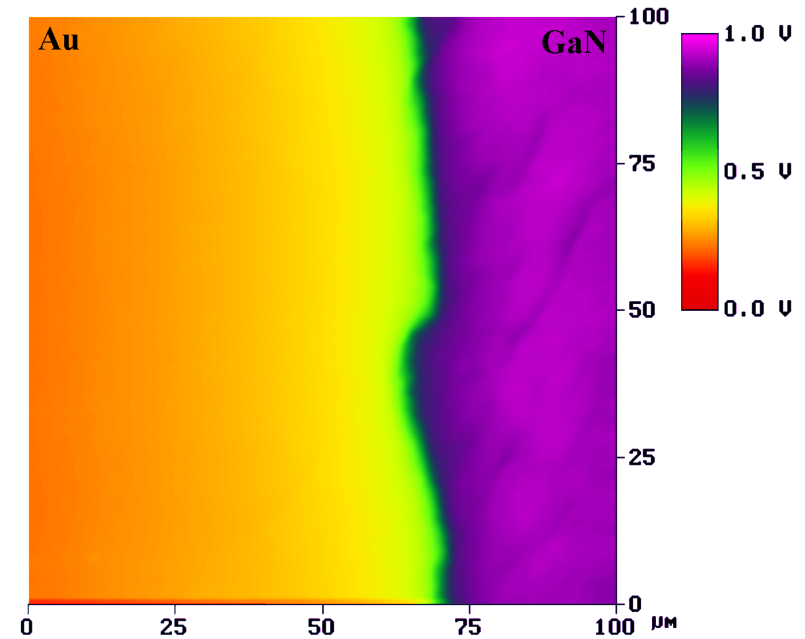
GaAs/(Ga,Mn)As

# Dioda Schottky'ego Au/GaN

(złącze metal-półprzewodnik)



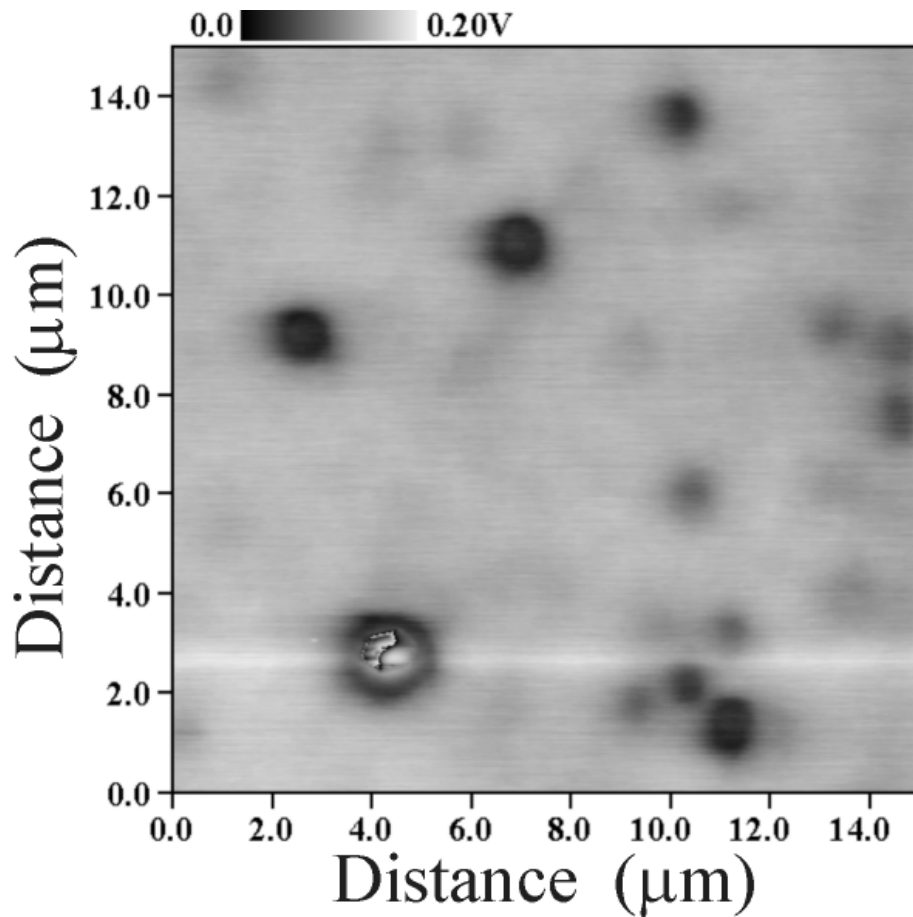
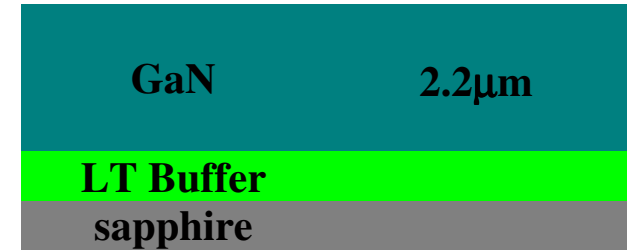
topografia



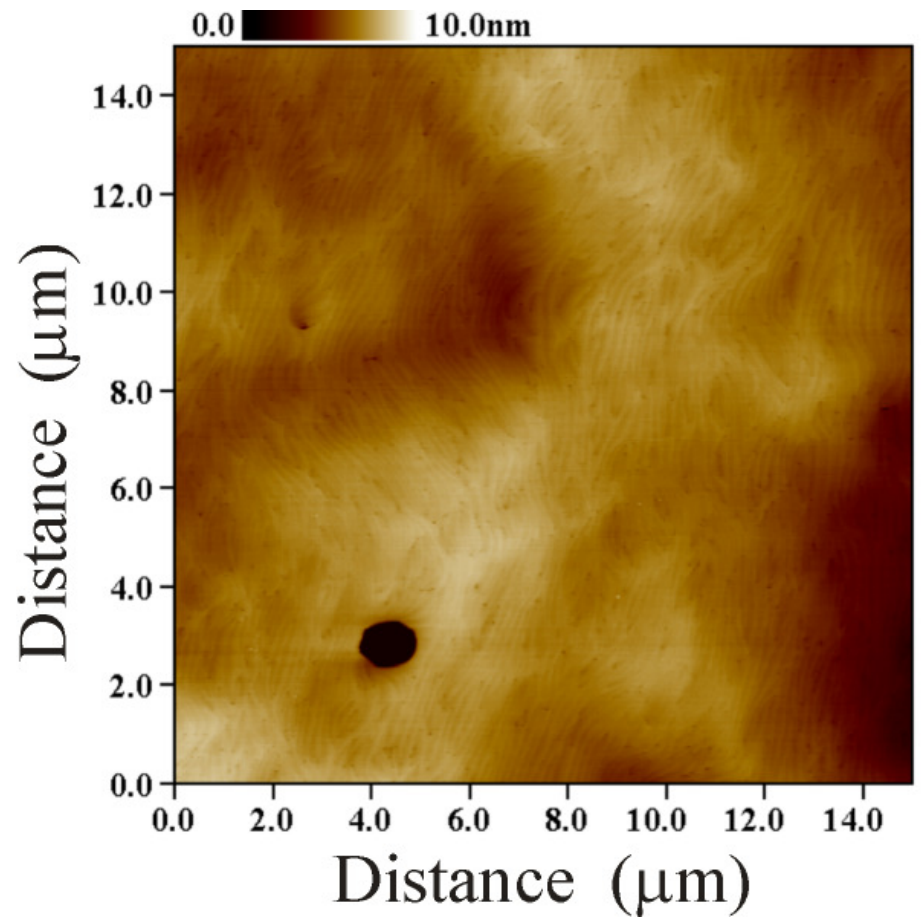
potencjał

granica półprzezroczystej warstwy Au

# GaN



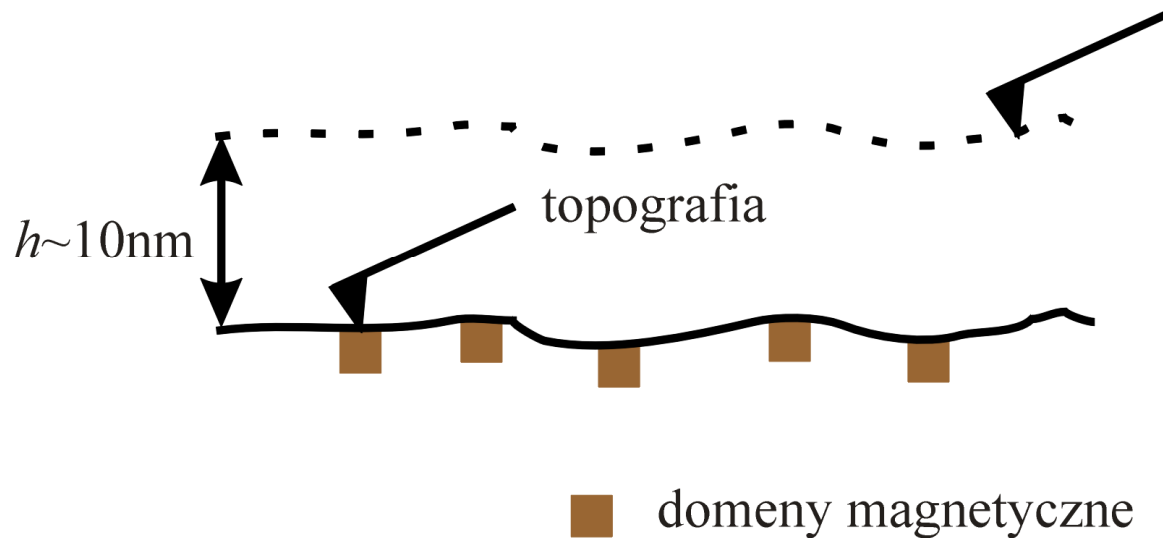
**potencjał (KPFM)**



**topografia (AFM)**

Rafał Bożek (Wydział Fizyki UW)

# MFM – Magnetic Force Microscopy

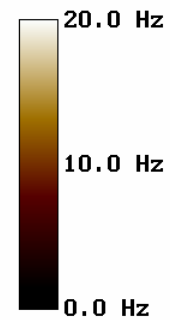
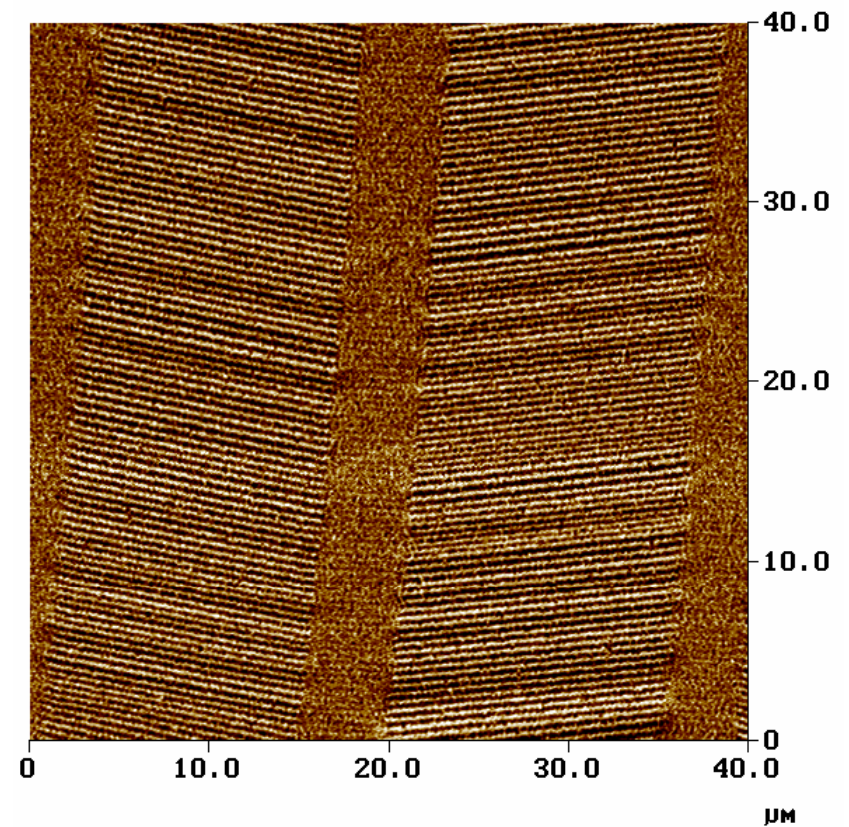
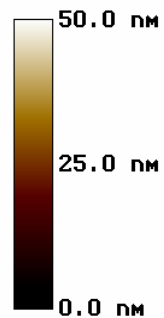
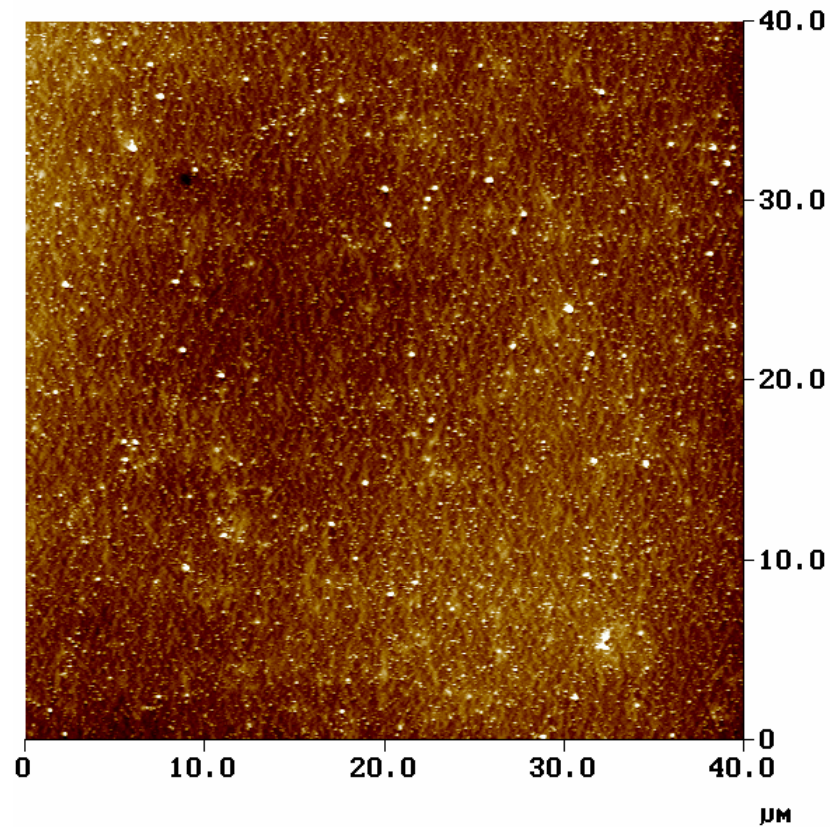


$$F(x) = F(x_0) + (x - x_0) \frac{\partial F}{\partial x} + \dots \quad \Delta\omega_0 = \frac{1}{2} \frac{\partial F}{\partial x} \frac{\omega_0}{k}$$

Siła magnetyczna (gradient)  $\Leftrightarrow$  zmiana częstości rezonansowej

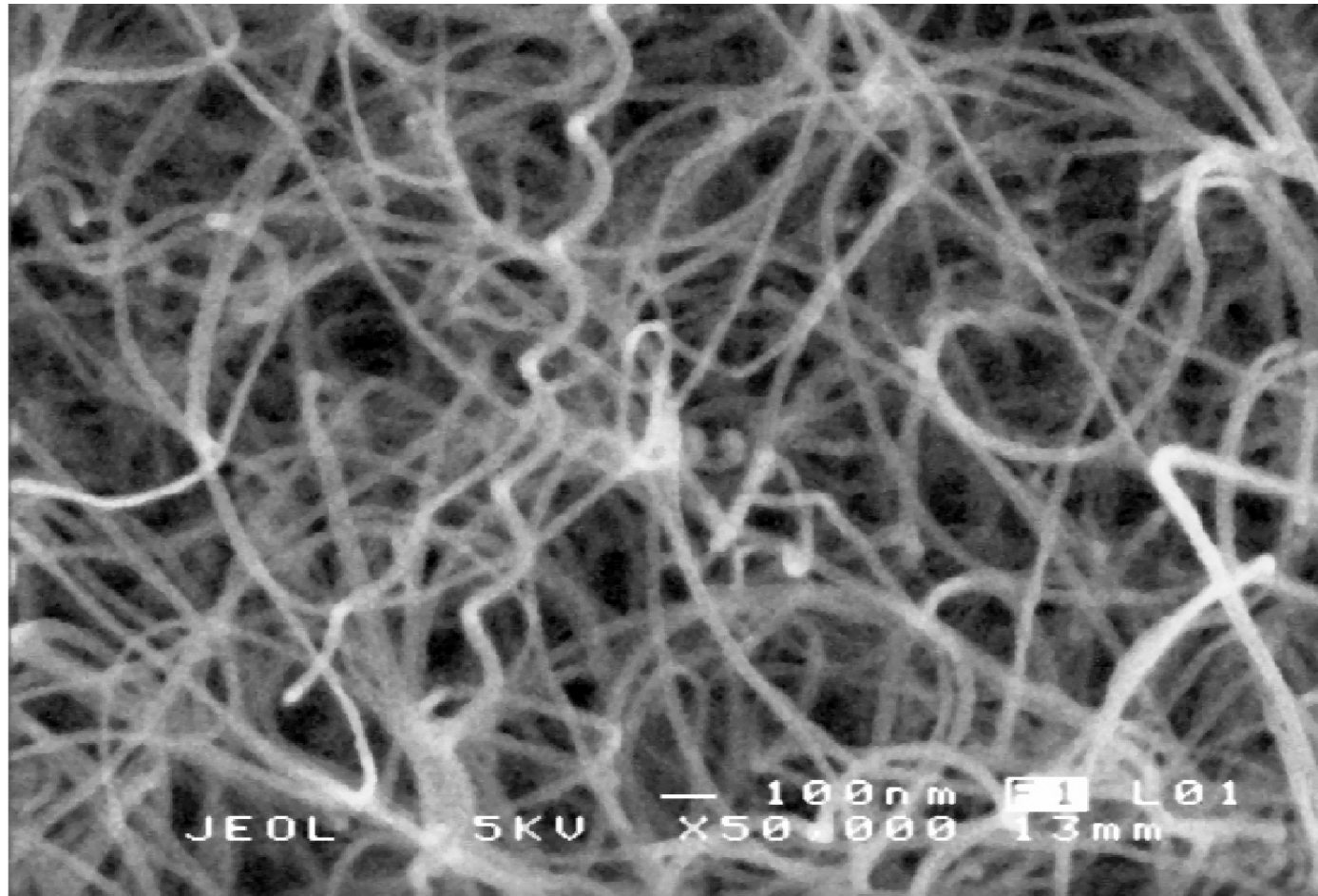
Pętla sprzężenia zwrotnego: utrzymanie rezonansu

# Mikroskop sił magnetycznych (MFM)



Rafał Bożek (Wydział Fizyki UW)

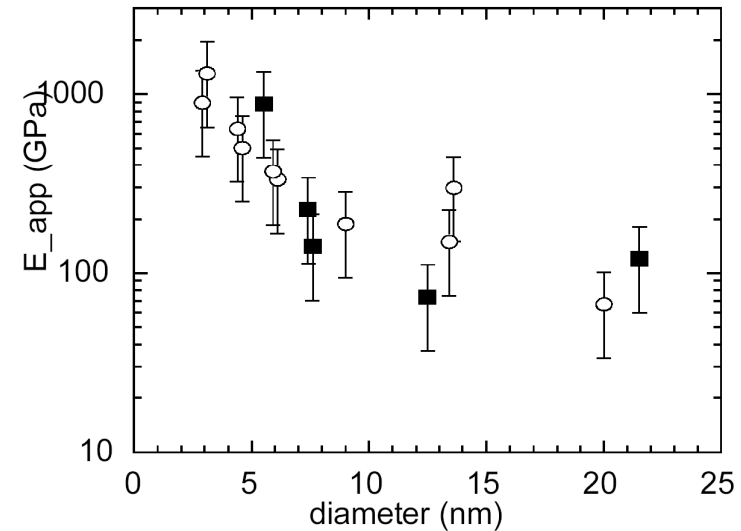
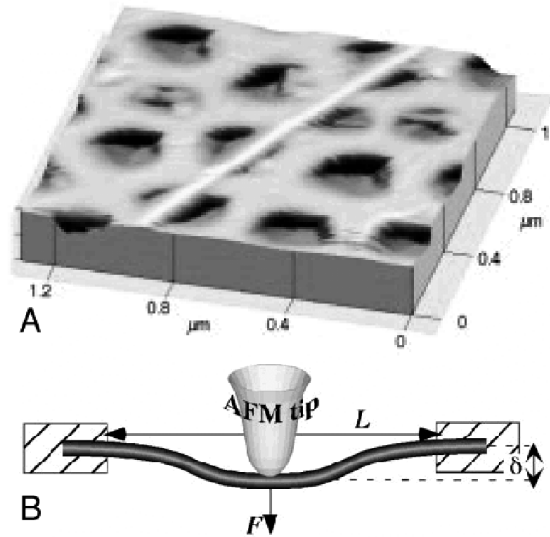
## Nanorurki węglowe



**Figure 3.** Scanning electron (SEM) micrographs of MWNT

L. Forrero et al. *Electronic and mechanical properties of carbon nanotubes,*

# Moduł Younga dla nanorurki?



$$F = 10^{-12} - 10^{-8} \text{ N}$$

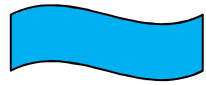
Figure 5. Dependence of the apparent Young's modulus ( $E_{app}$ ) on the diameter of SWNT bundles measured using AFM. The untreated bundles are represented by the open circles and the hydrogenated and irradiated bundles by the filled squares.

L. Forrero et al. *Electronic and mechanical properties of carbon nanotubes* (Wikipedia)

A. Volodin et al., Phys. Rev. Lett. **84**, 3342 (2000)

Palaci et al., Phys. Rev. Lett. **94**, 175502 (2005)





## Wykład 12

# Porównanie mikroskopów

	Mikroskop optyczny	STM	AFM
Rozdzielczość: x, y	1.0 $\mu\text{m}$	0.1 nm	2 – 10 nm
Rozdzielczość: z	-	0.01 nm	0.1 nm
Powiększenie	$10^3$	$10^8$	$10^8$
próbka	próbka przezroczysta	nierówności < 10 $\mu\text{m}$	nierówności < 10 $\mu\text{m}$