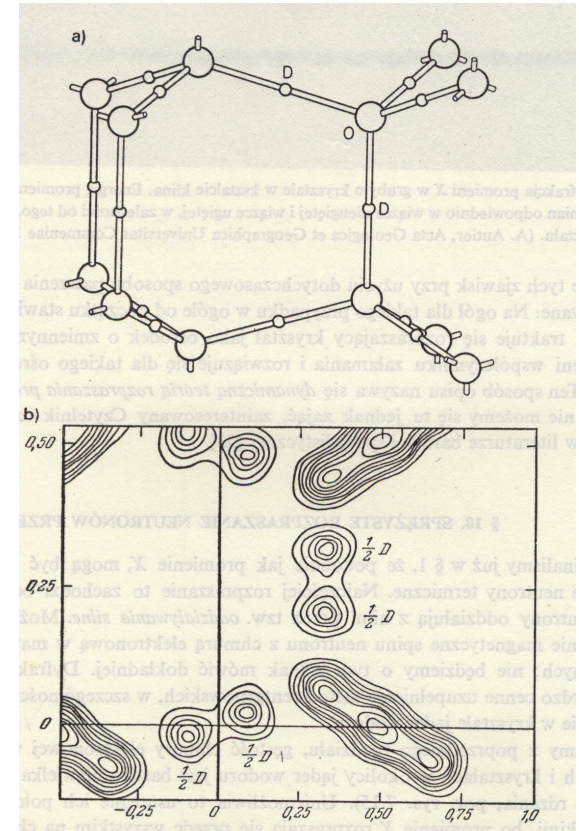
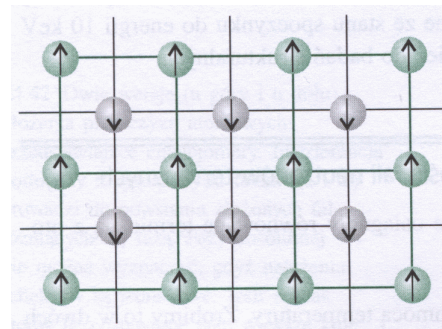


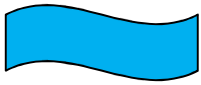
Wykład 12

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.

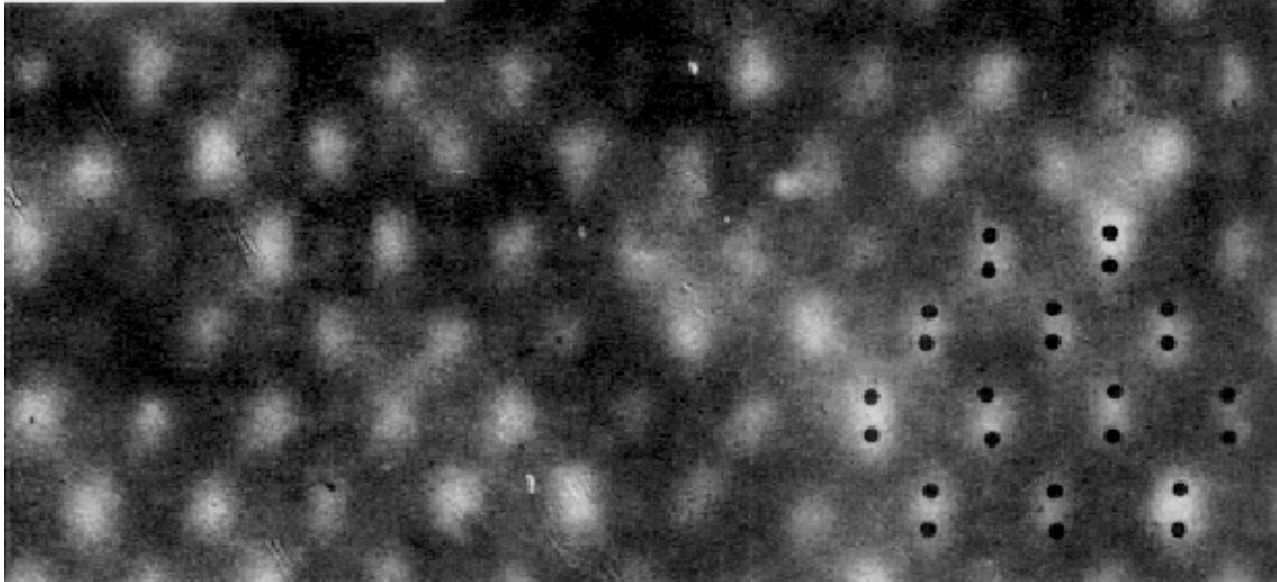
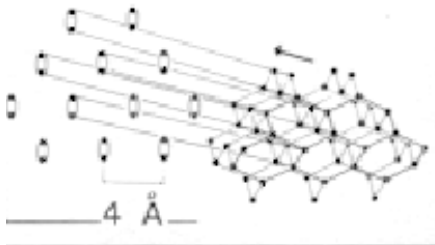


J. Ginter

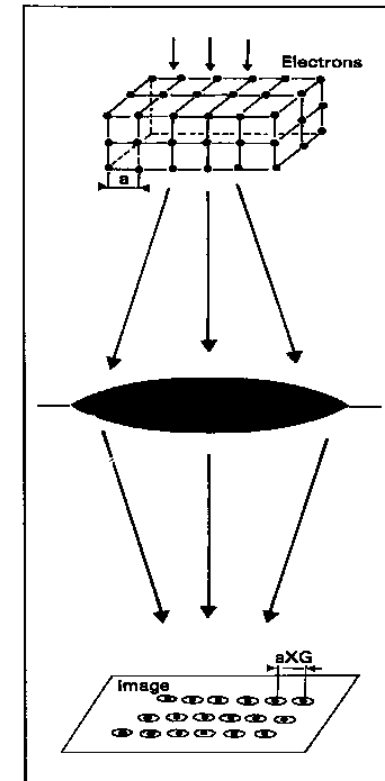


Wykład 12

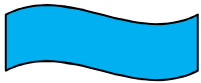
- ▶ Elektrony mają ładunek elektryczny i oddziałują silnie z materią, wnikają bardzo płytko.
- ▶ Zjawisko ugięcia elektronów pozwala na badania strukturalne powierzchni oraz bardzo cienkich warstw



Elektrony

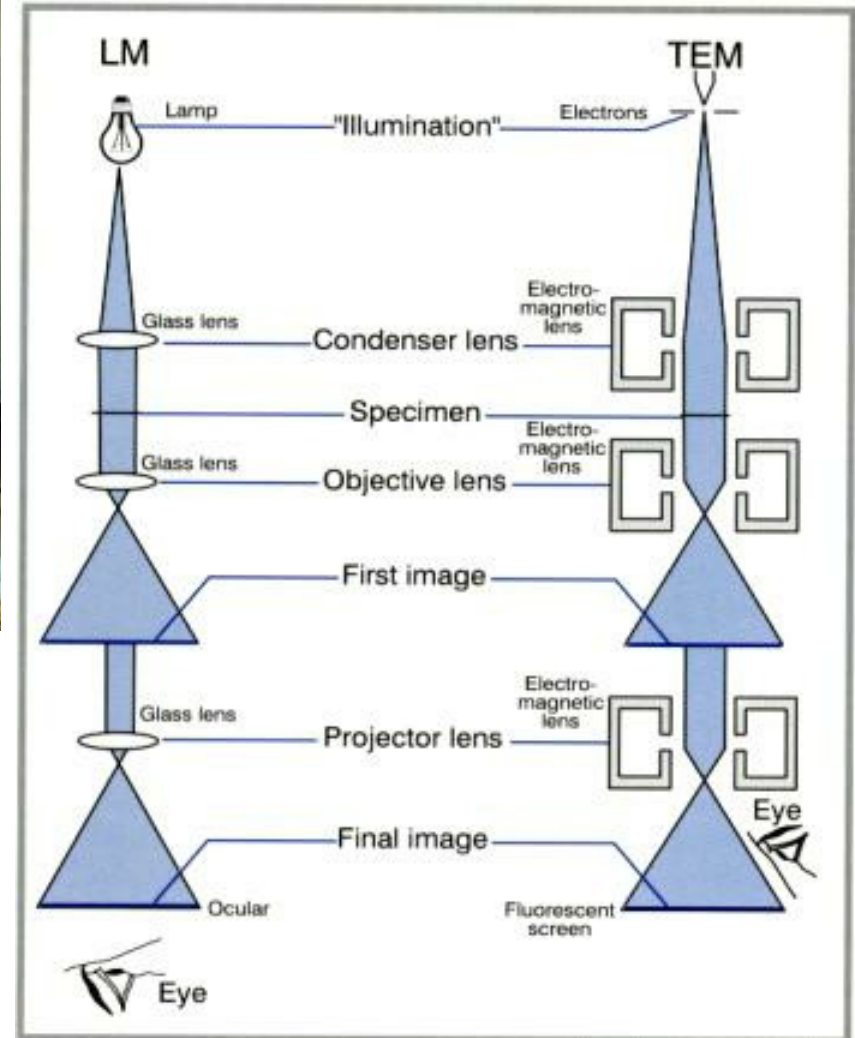


T. Stacewicz & A. Witowski

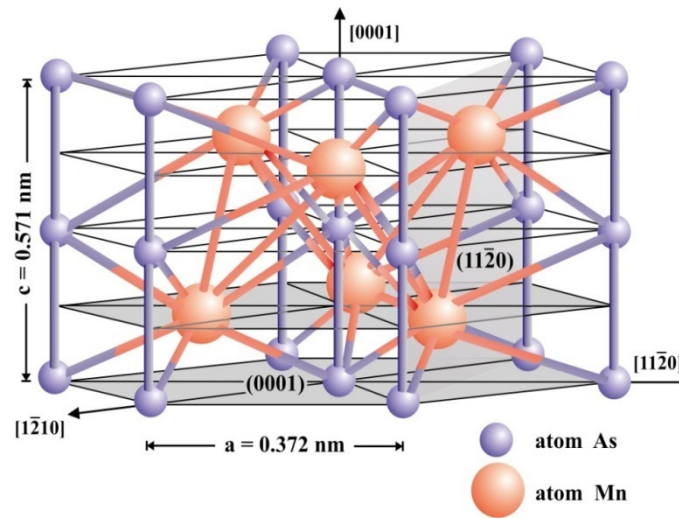
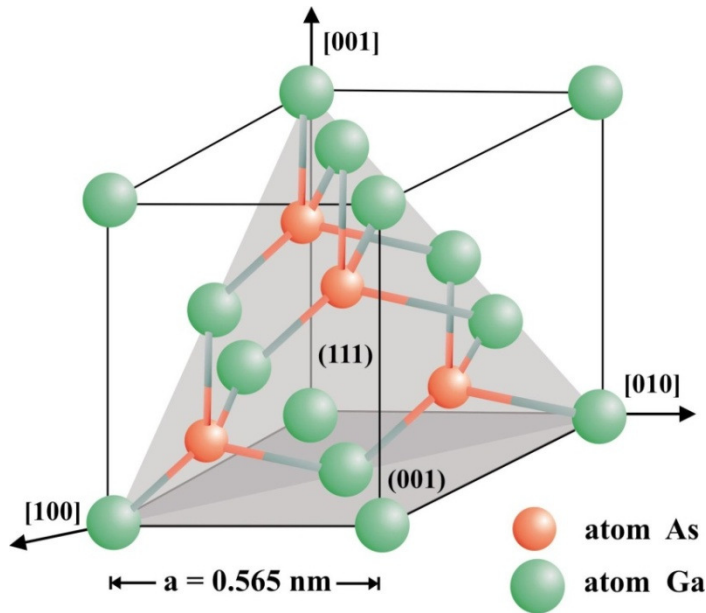


Wykład 12

Transmisyjny Mikroskop Elektronowy (TEM)

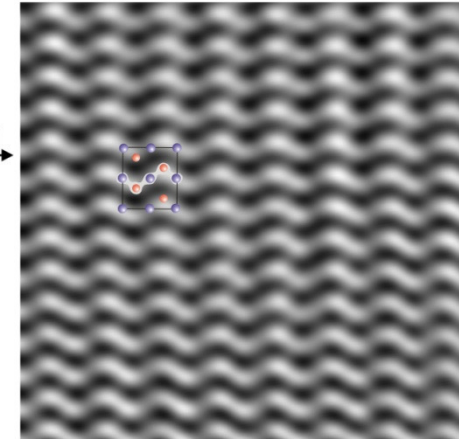


Transmisyjny mikroskop elektronowy (SEM)

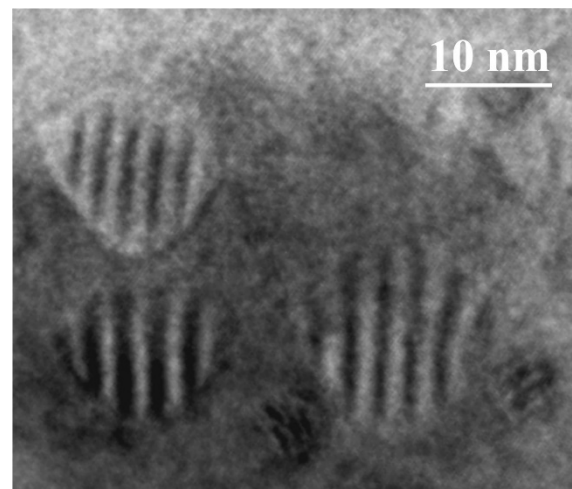
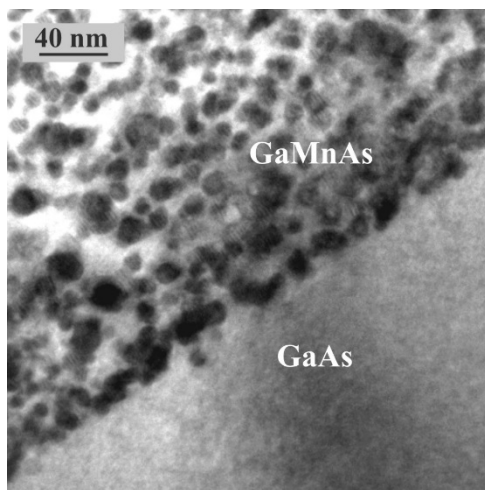
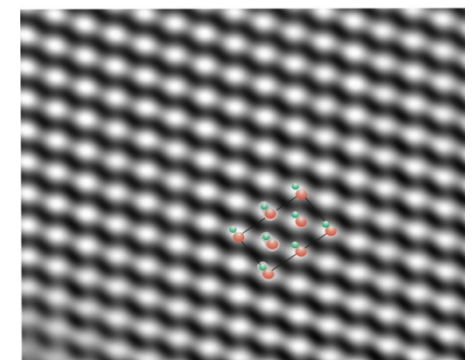


HRTEM
High Resolution
TEM)

MnAs - PŁASZCZYZNA (1120)



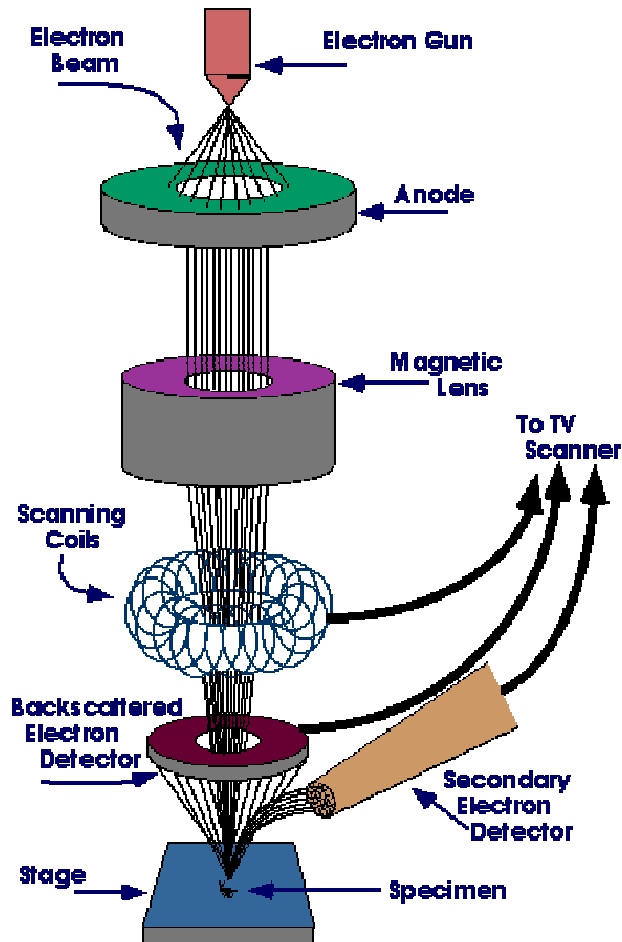
GaAs - PŁASZCZYZNA (110)



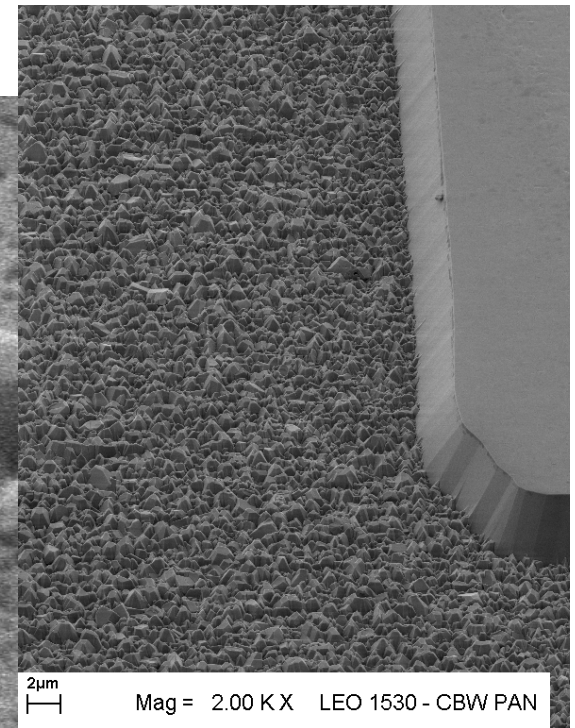
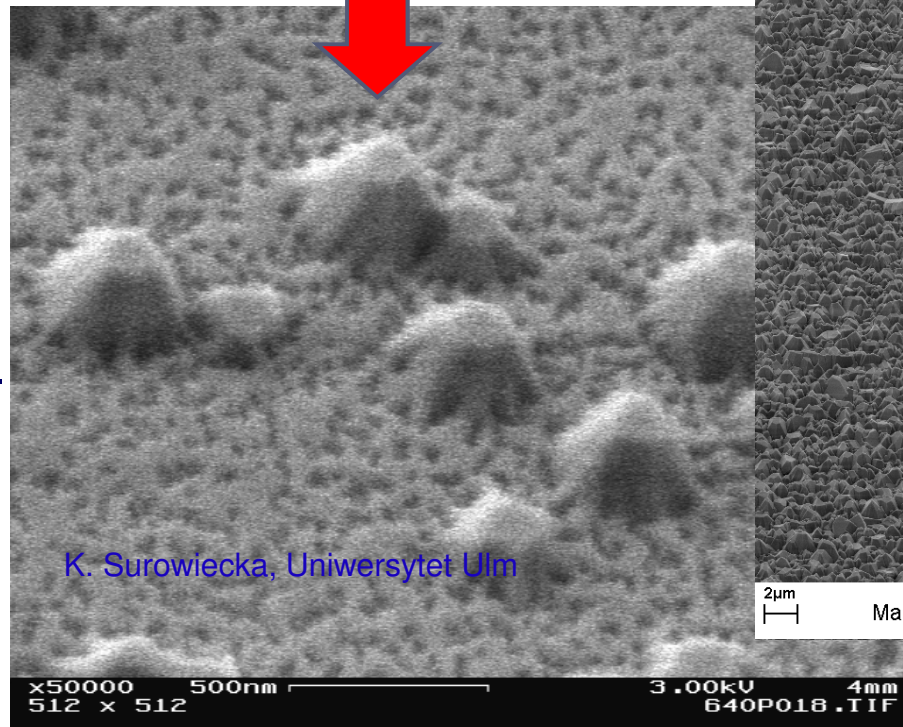
J. Borysiuk

Skaningowy mikroskop elektronowy (SEM)

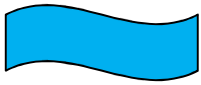
Wykorzystujemy skanowanie powierzchni próbki przez wąską wiązkę elektronów. Elektrony rozpraszają na powierzchni tak jak światło...



Kropki kwantowe GaN/AlGaN

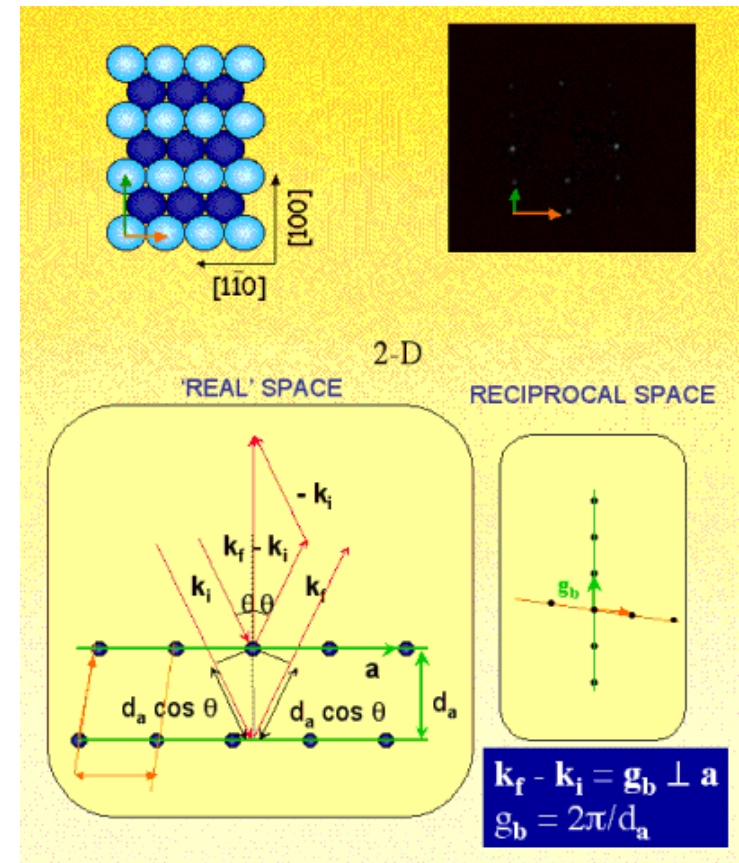
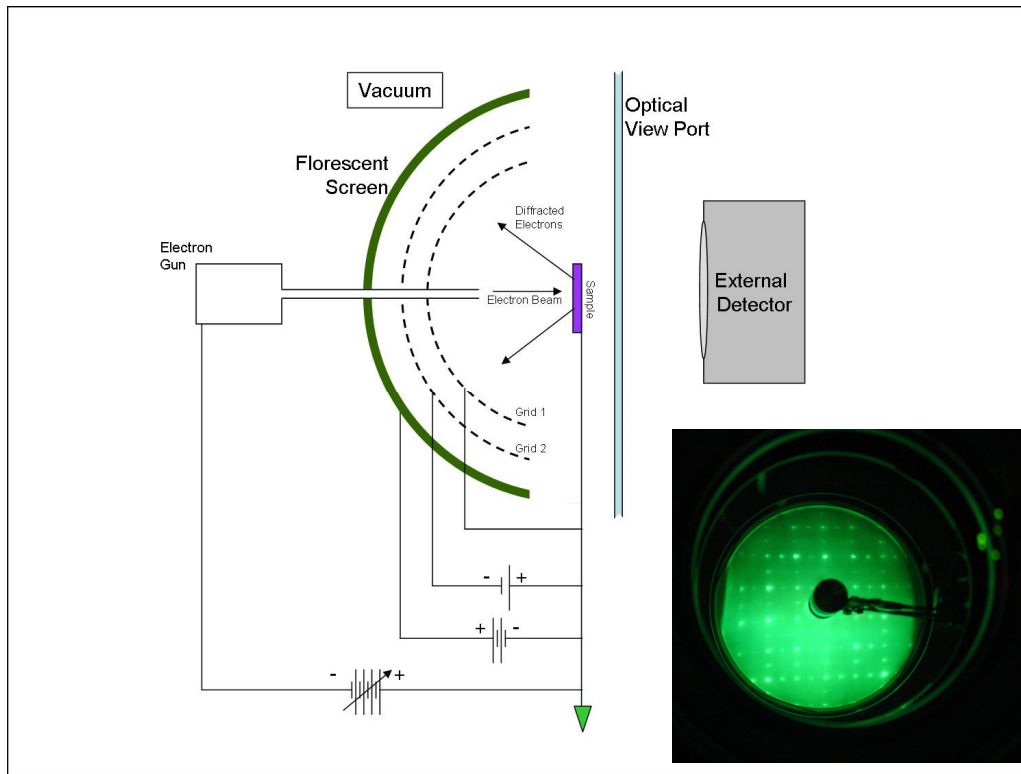


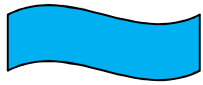
Warstwa epitaksjalna GaAs (wzrost 2D)
w sąsiedztwie krystalitów GaAs (wzrost 3D)
Wzrost - K. Pakuła (UW)



Wykład 12

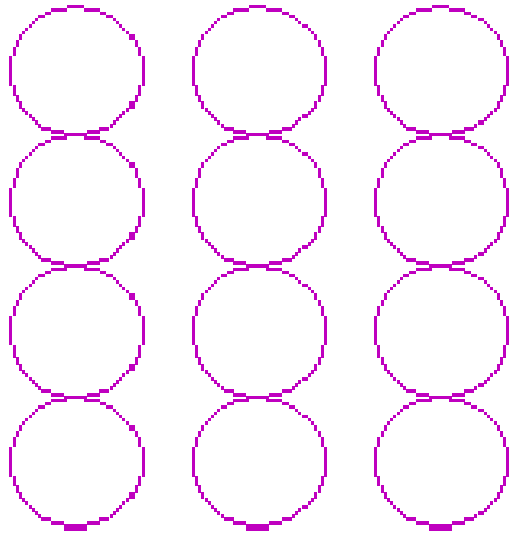
Dyfrakcja nisko-energetycznych elektronów (LEED)



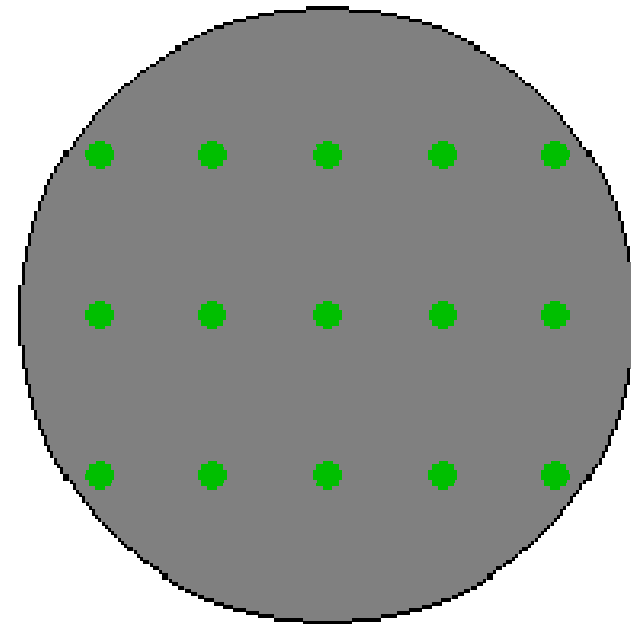


Dyfrakcja nisko-energetycznych elektronów (LEED)

Real Space - fcc(110) surface

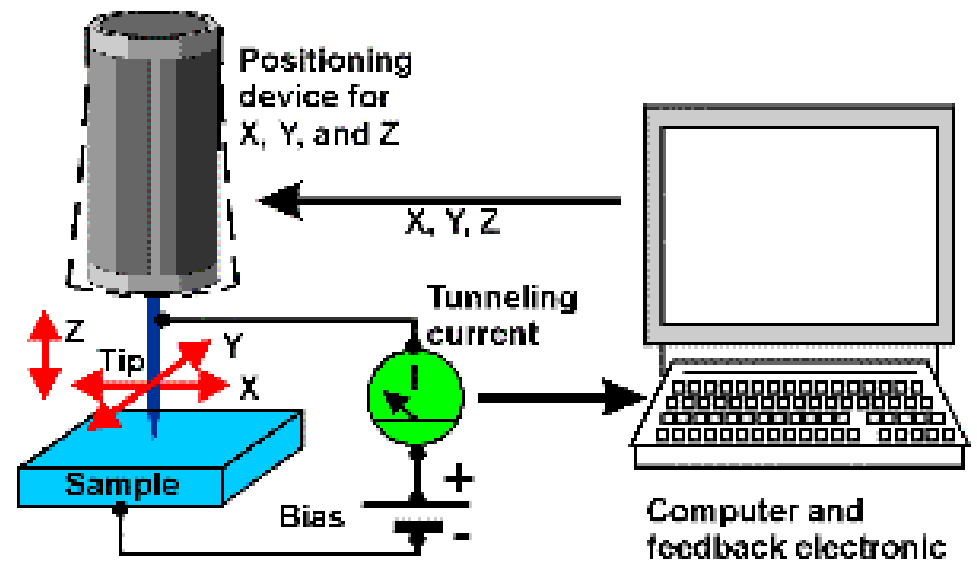


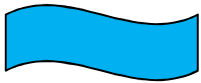
Diffraction Pattern



Wykład 11

Skaningowy Mikroskop Tunelowy (STM)





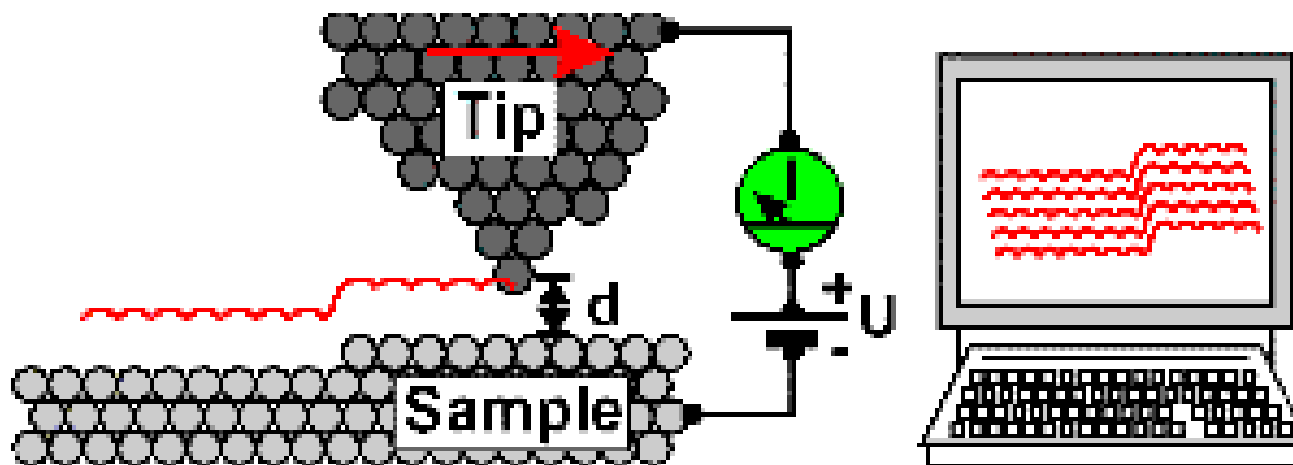
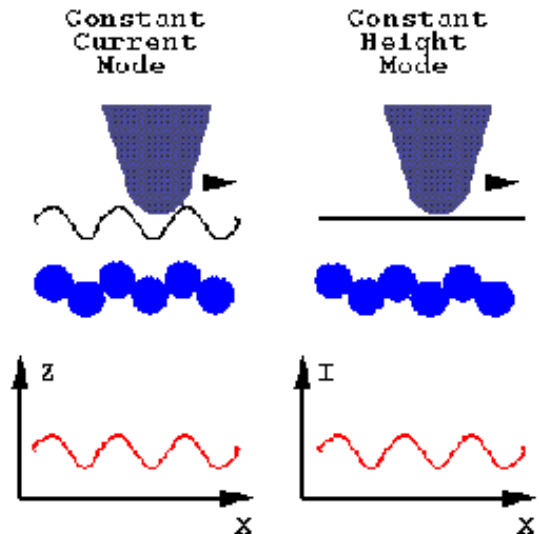
Wykład 11

Skaningowy Mikroskop Tunelowy (STM)

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

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

Φ – 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

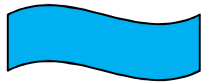
Andre Geim



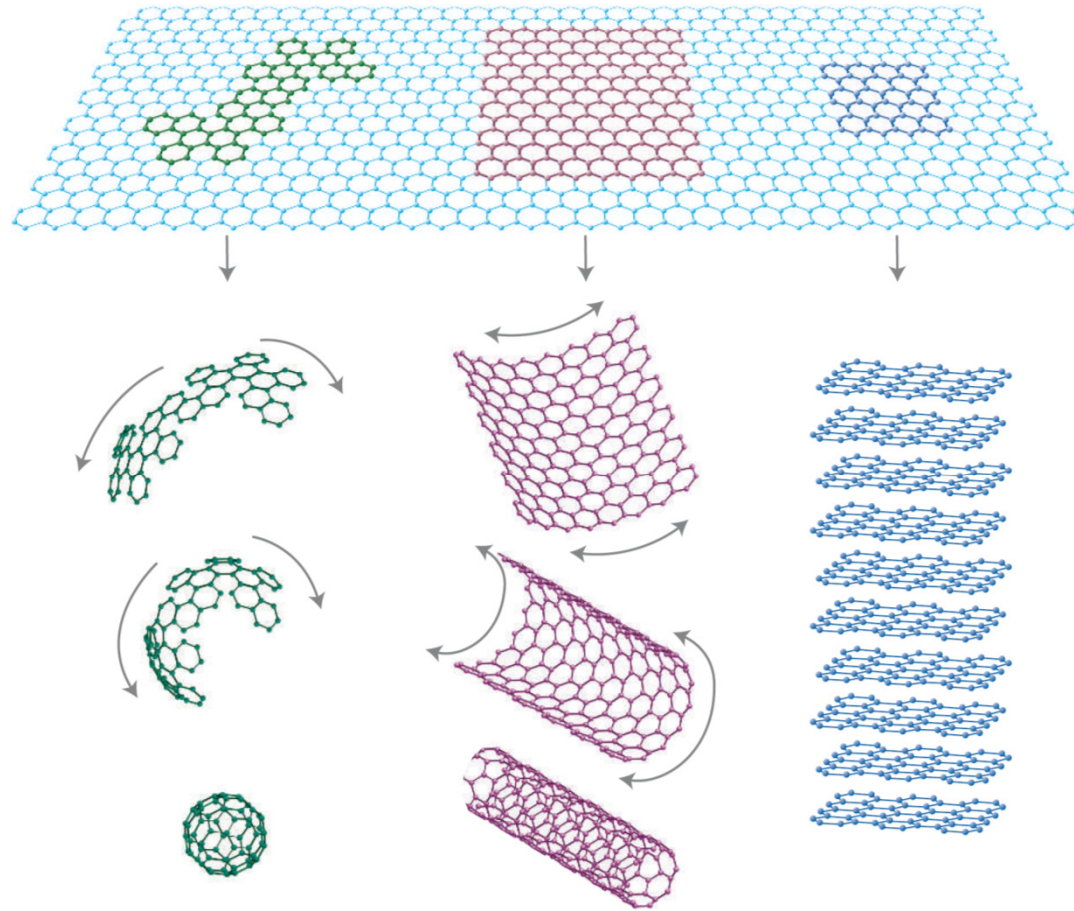
Photo: University of Manchester, UK

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

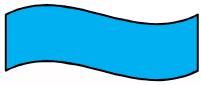


fulereny

nanorurki

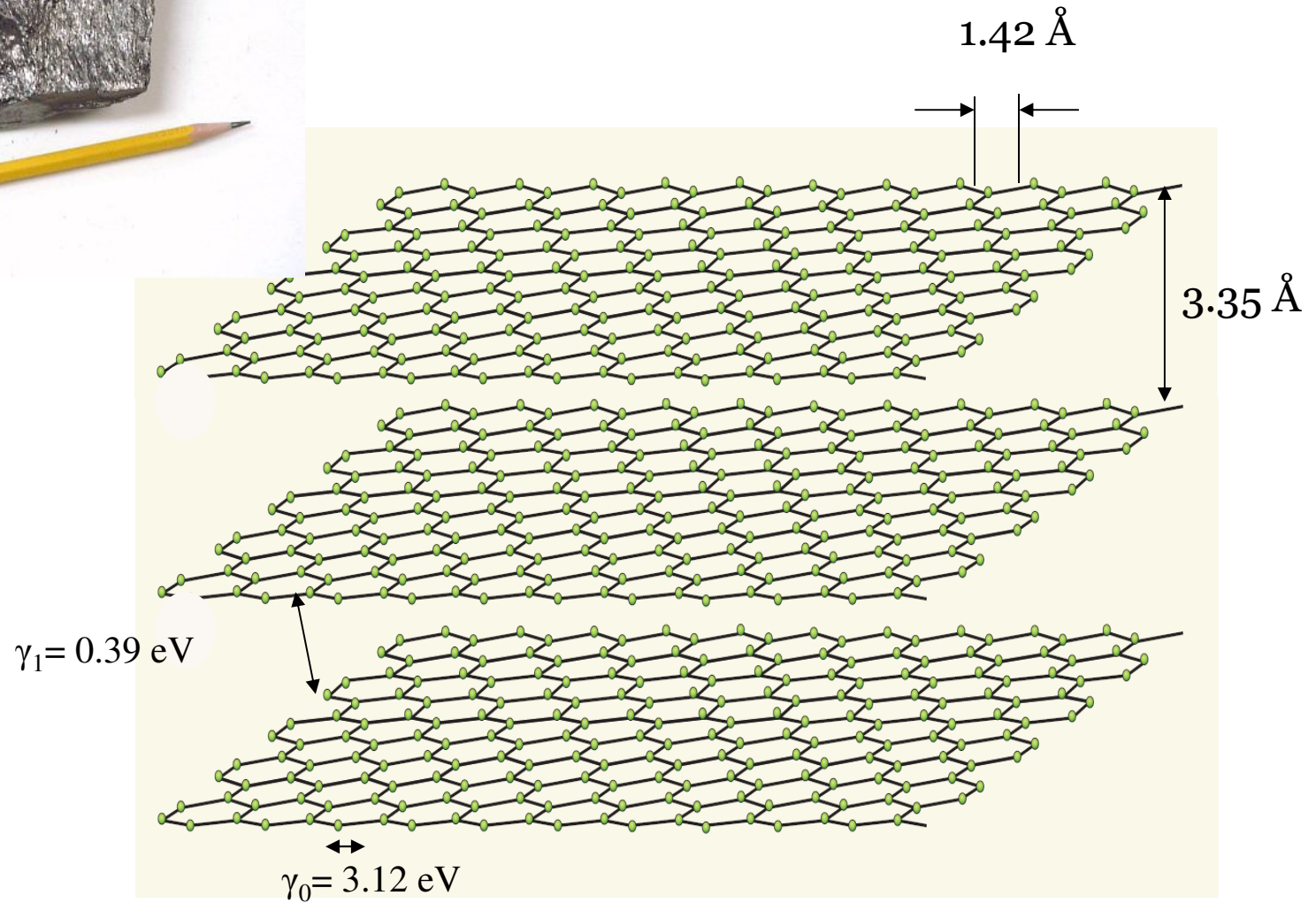
grafit

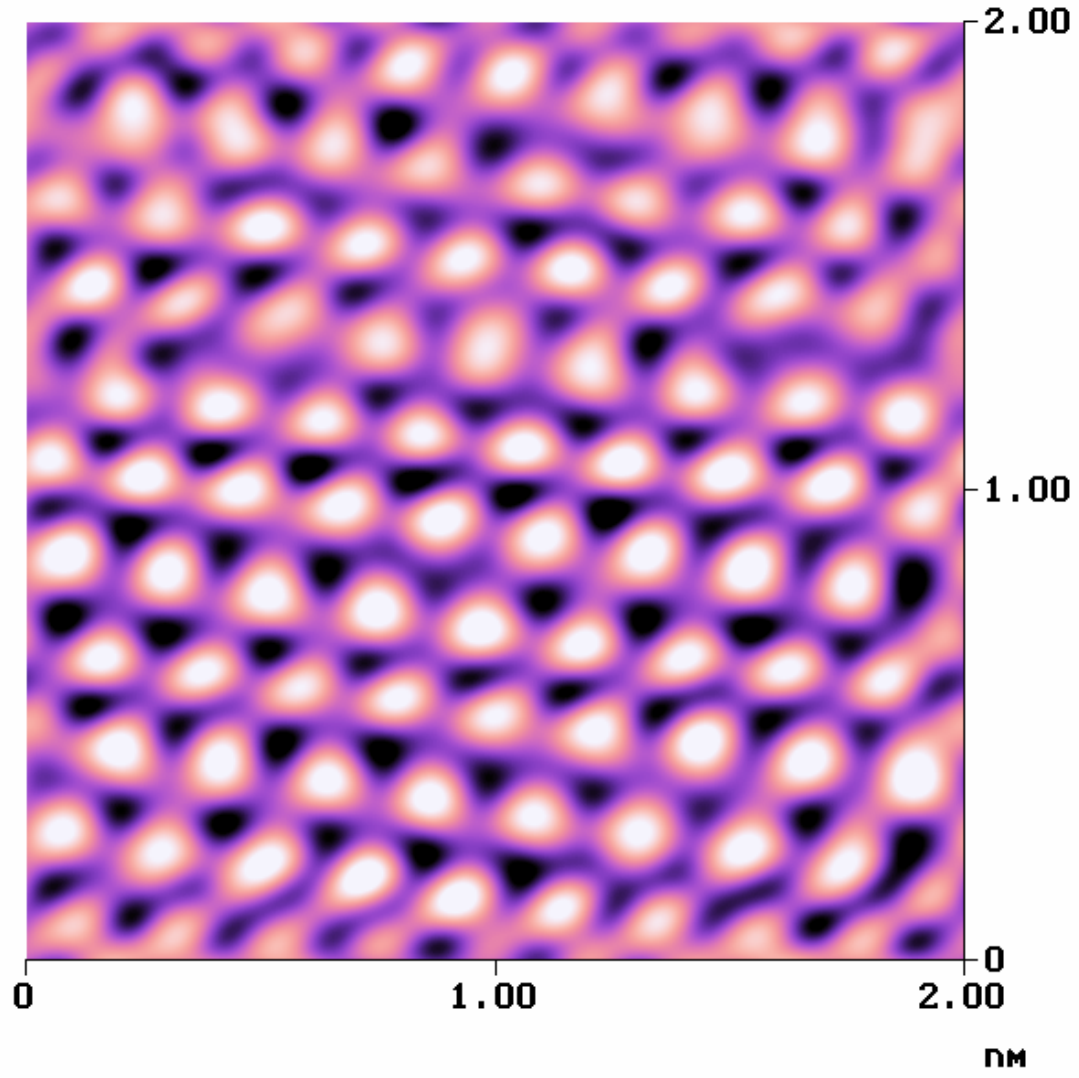
Podstawowy budulec dla struktur węglowych....



Wykład 12

Grafit

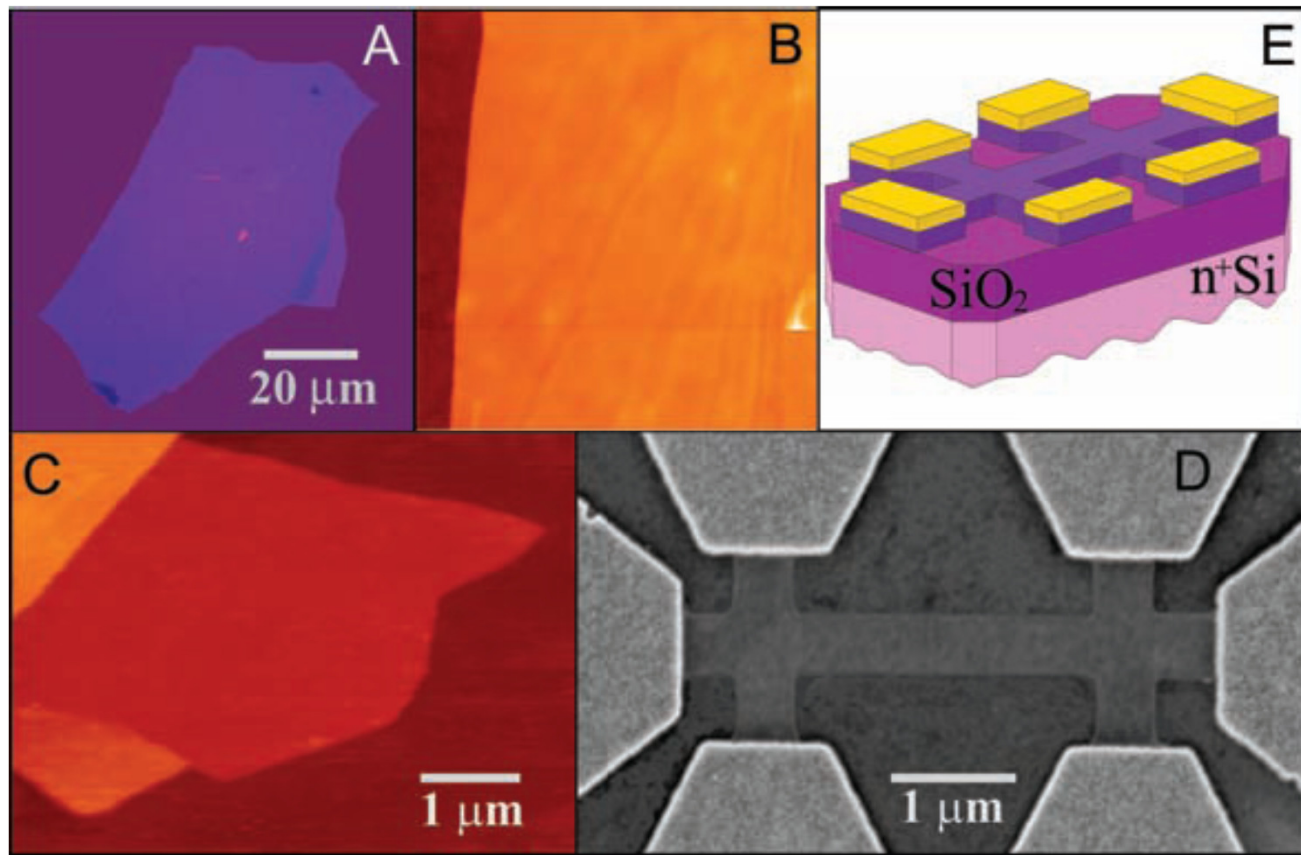




Digital Instruments NanoScope
Scan size 2.000 nm
Scan rate 54.93 Hz
Number of samples 512
Image Data Current
Data scale 1.000 nA

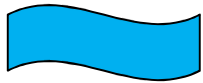
grafit1.001

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

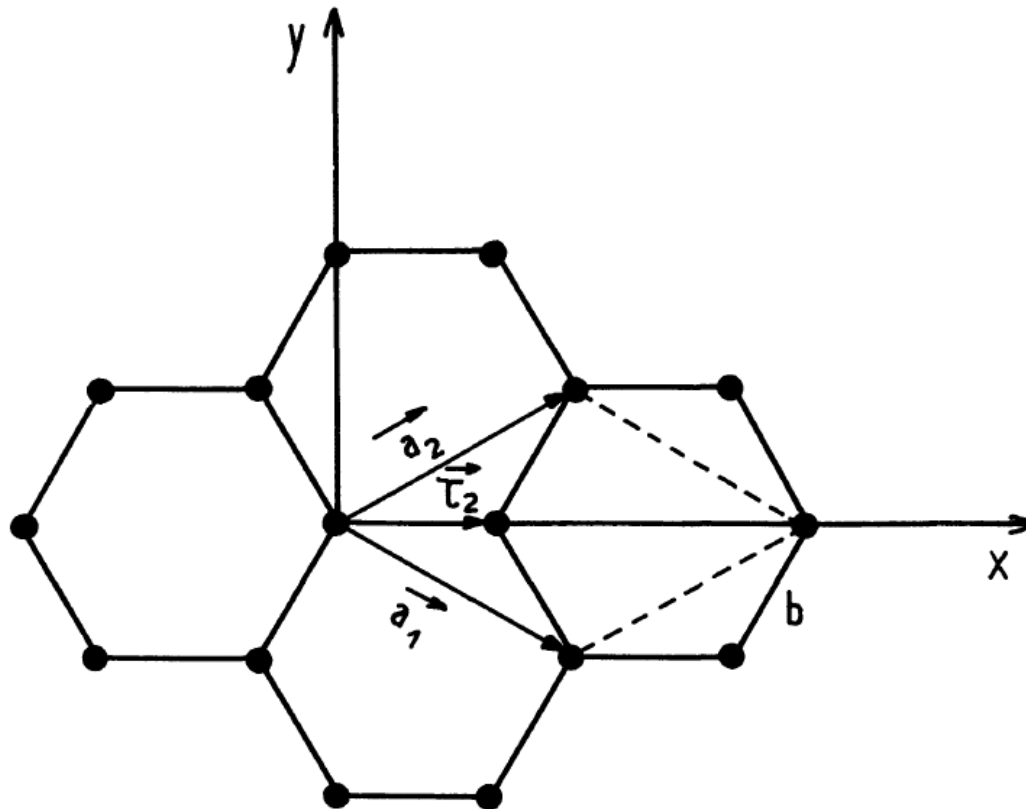
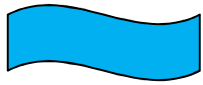


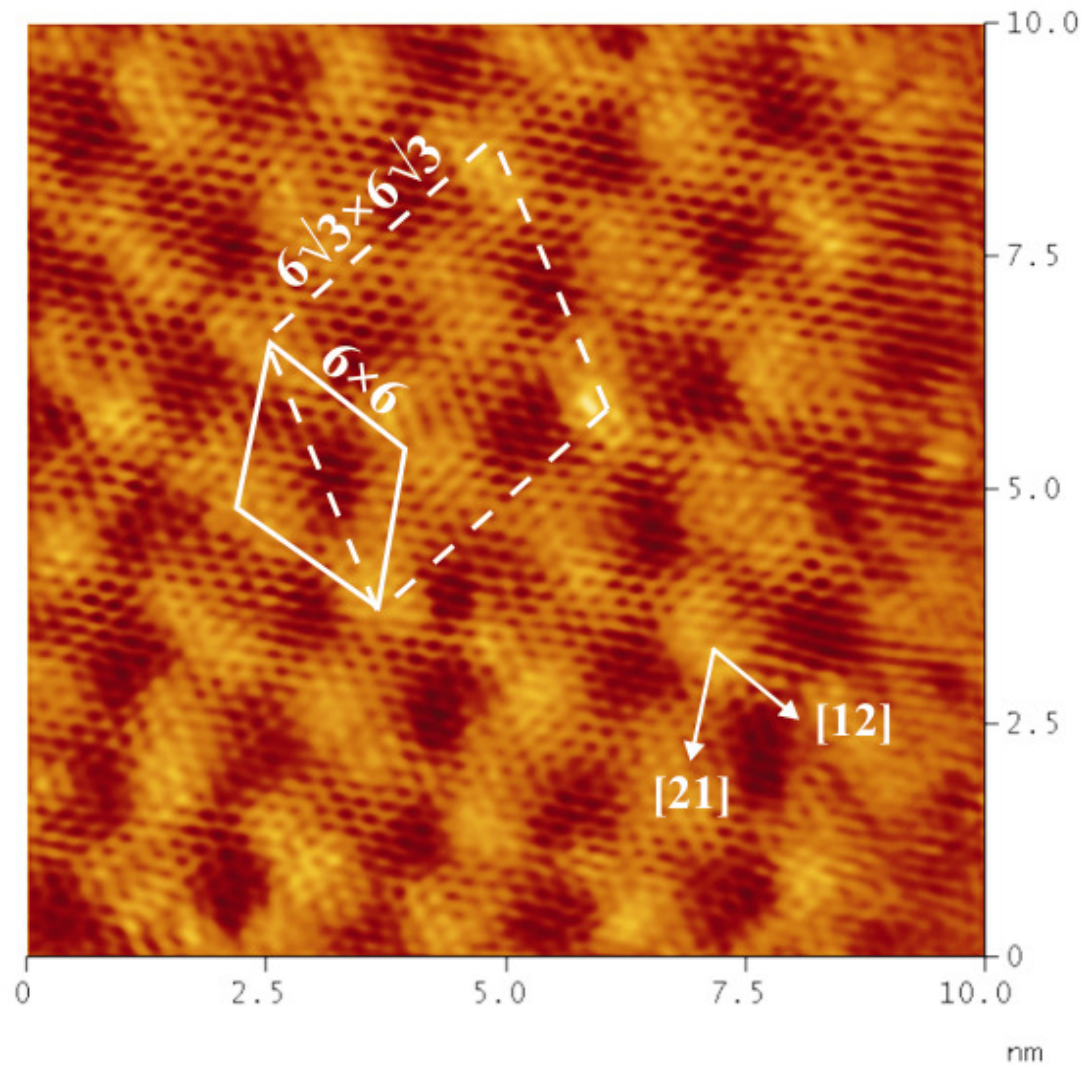
Fig. 1. — Unit cell of a single graphite layer.

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

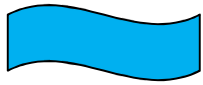


Wykład 12

Mikroskop tunelowy (STM)

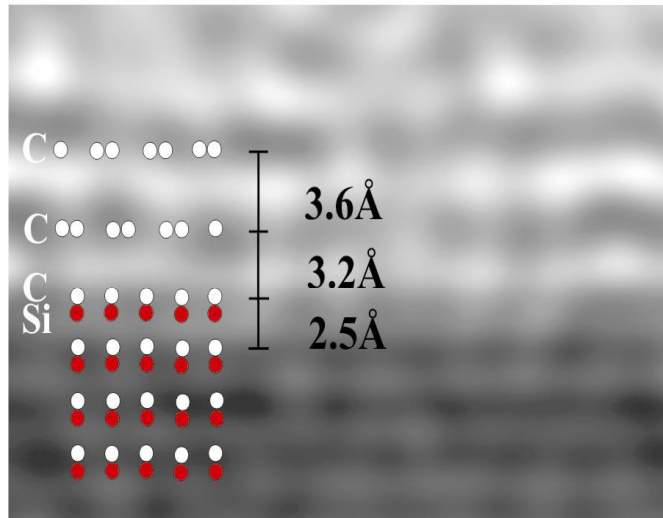
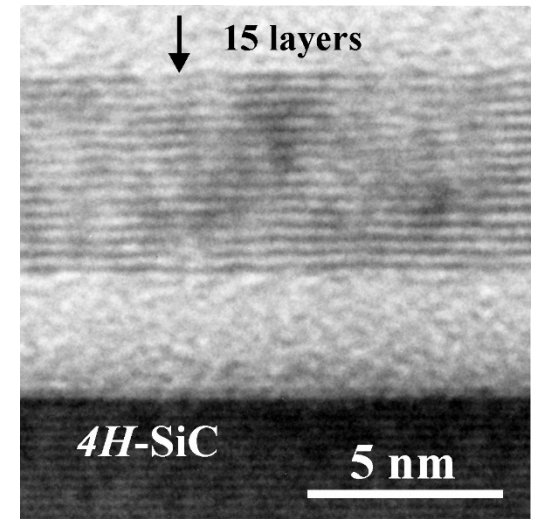


Grafen na podłożu 4H-SiC(0001), strona Si (R.Bożek)

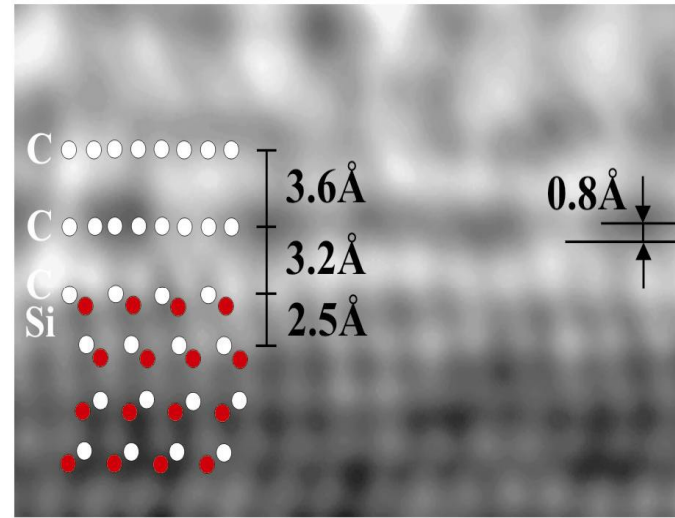


Wykład 12

Grafen - Elektronowy mikroskop transmisyjny
HRTEM (wysoka rozdzielczość)



[1100] sample orientation



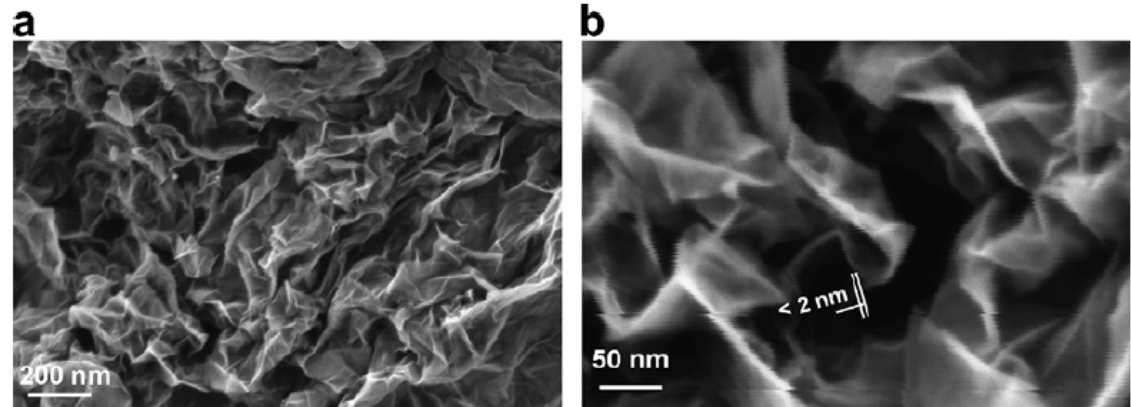
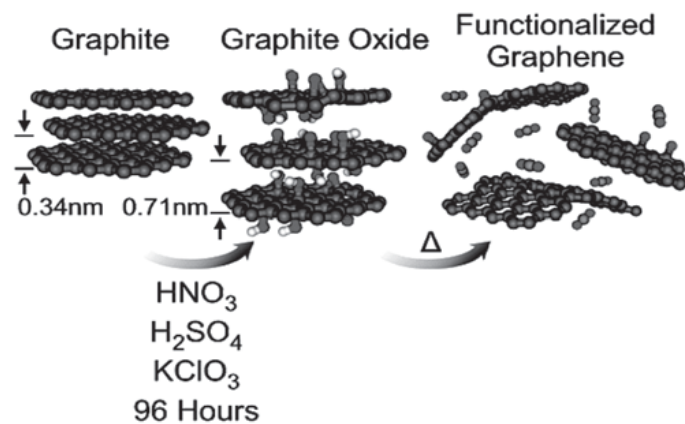
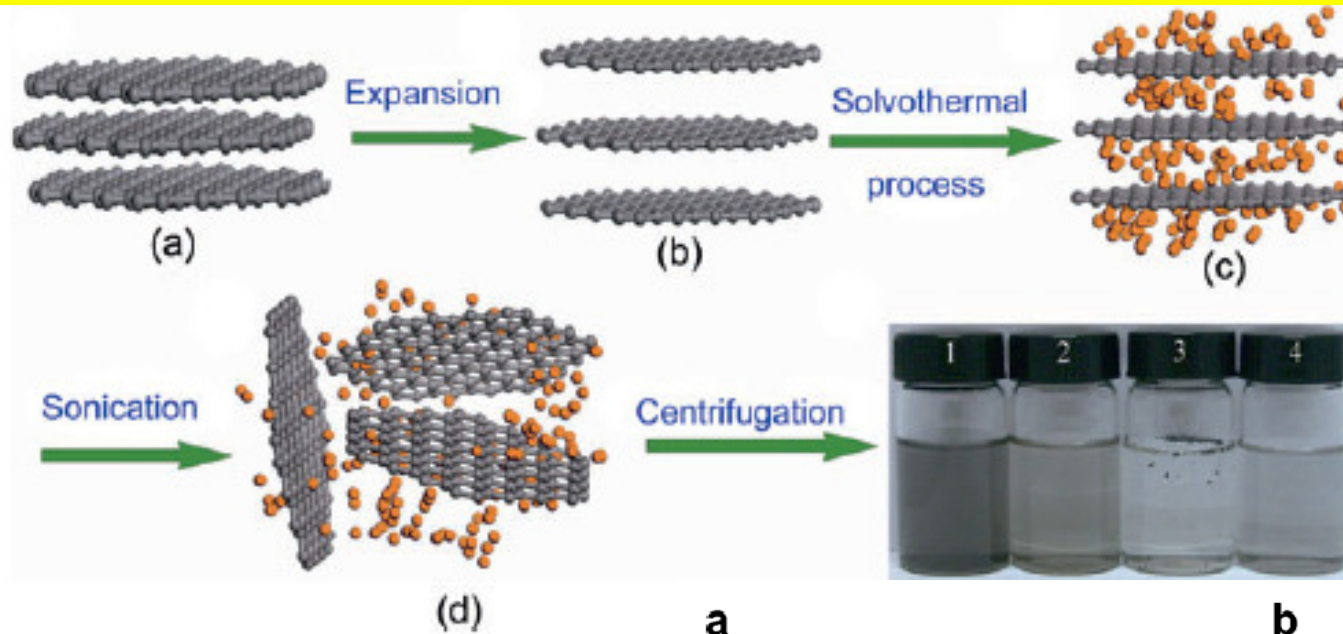
[1120]

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)

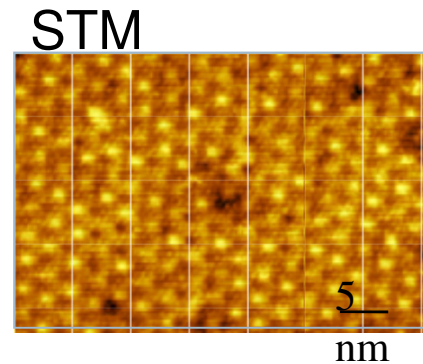
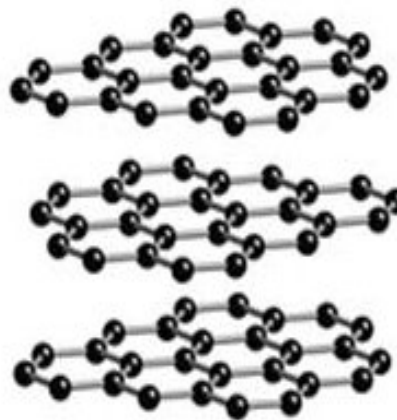
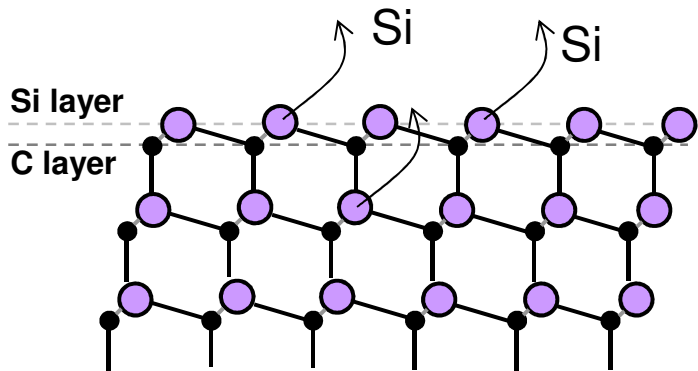
Obiecująca metoda otrzymywania grafenu...

Wgrzewanie SiC

T (>1400°C); wysoka próżnia

SiC

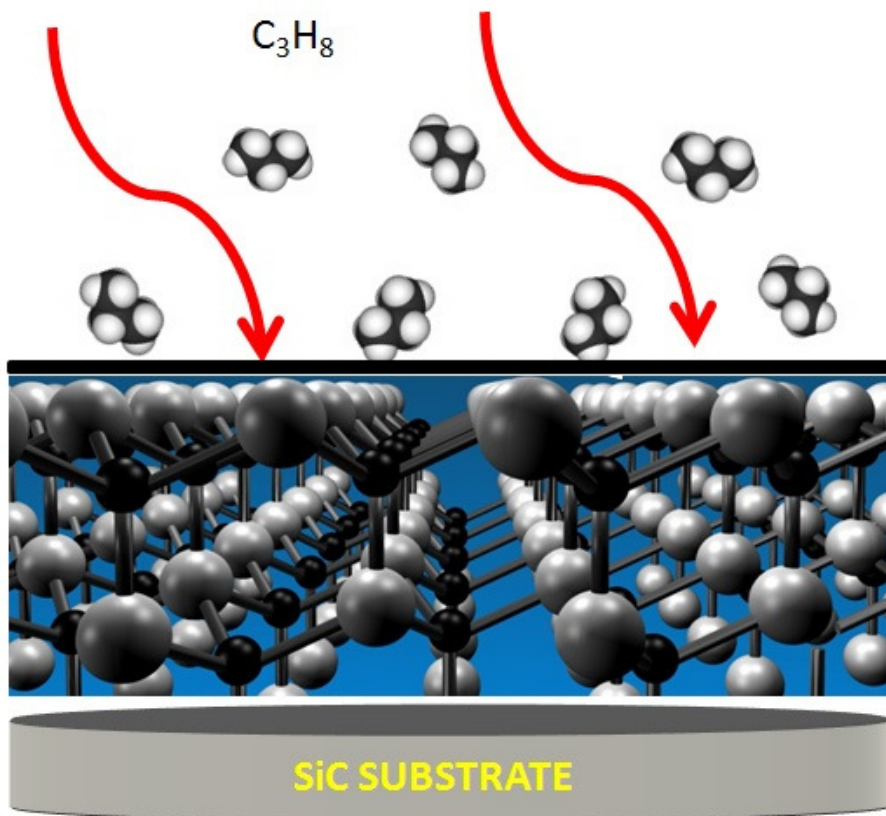
Kilka, kilkadziesiąt warstw węglowych



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



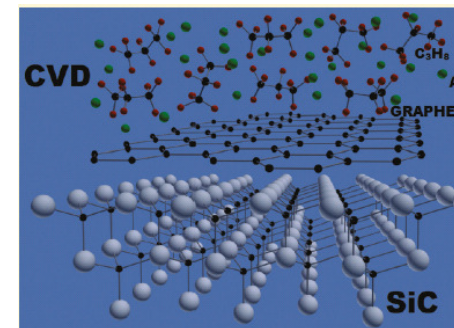
2006/2007



Nowy pomysł:
„prawdziwa epitaksja”
(osadzanie)

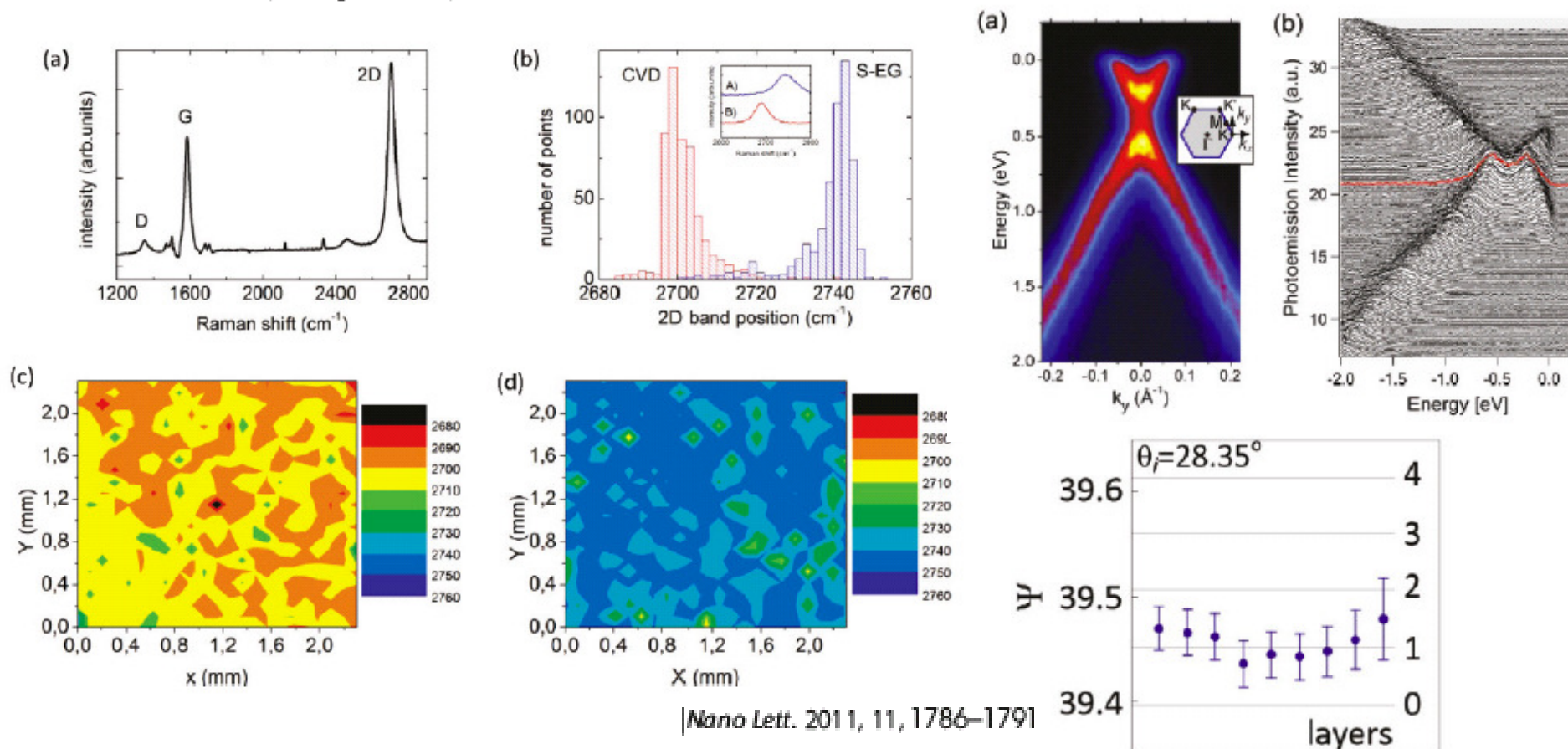
Zalety

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



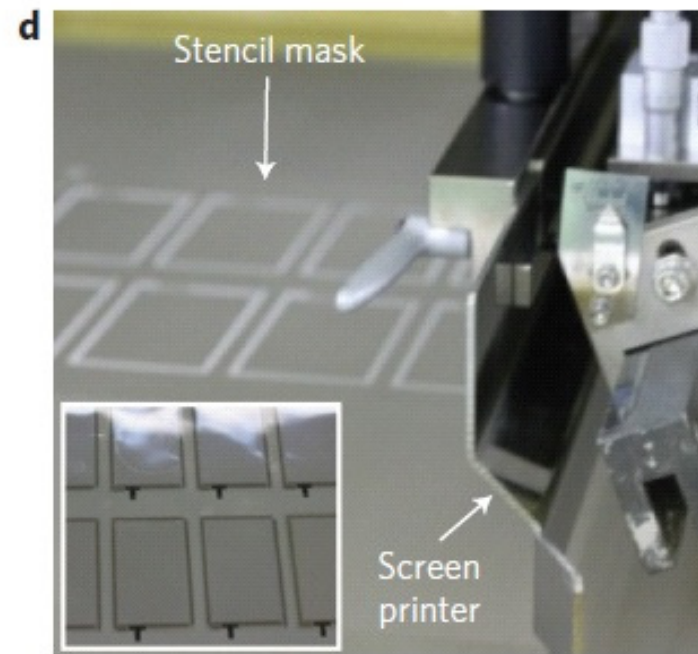
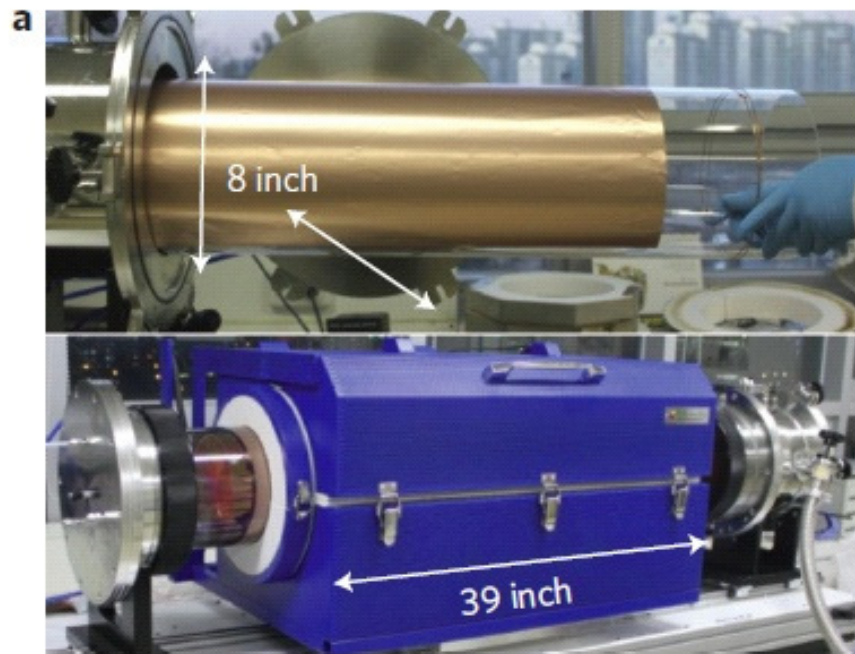
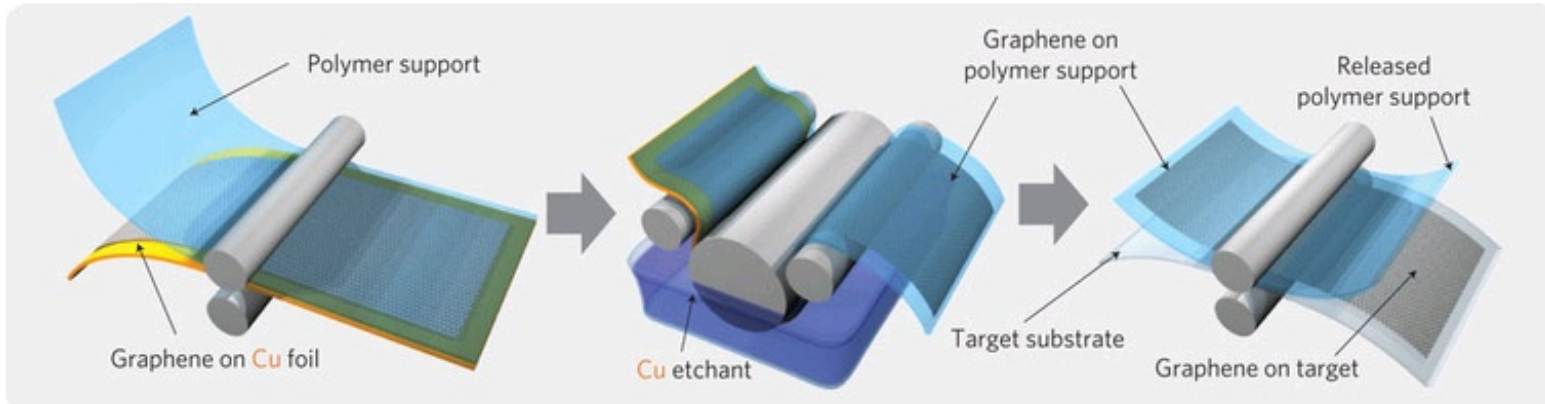
Graphene Epitaxy by Chemical Vapor Deposition on SiC

W. Strupinski,^{*1} K. Grodecki,^{1,2} A. Wyszomlek,² R. Stepniewski,² T. Szkopek,³ P. E. Gaskell,³ A. Grüneis,^{4,5} D. Haberer,⁴ R. Bozek,² J. Krupka,⁶ and J. M. Baranowski^{1,2}



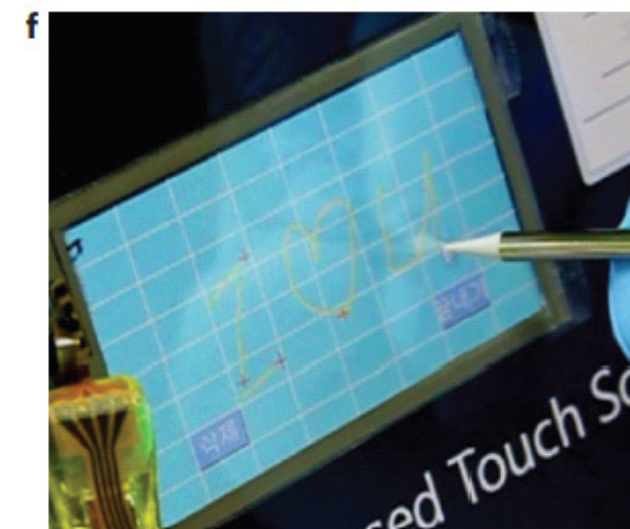
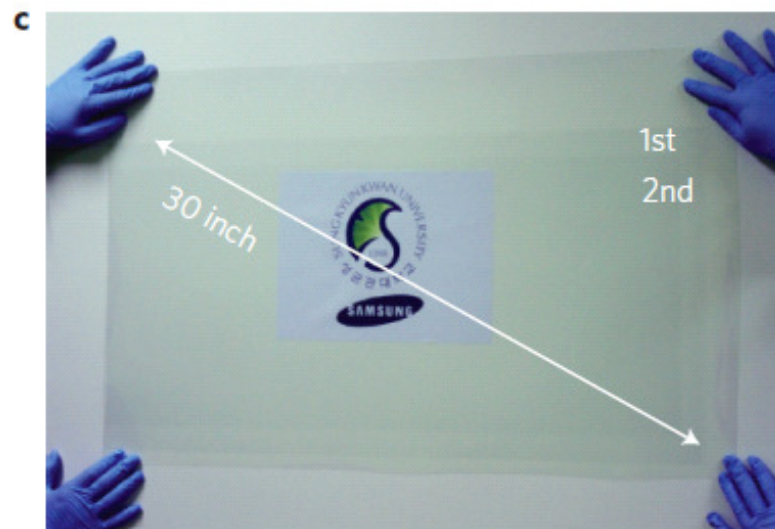
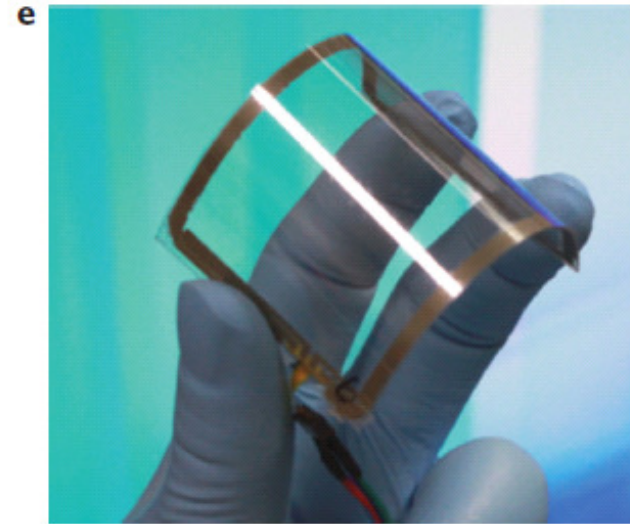
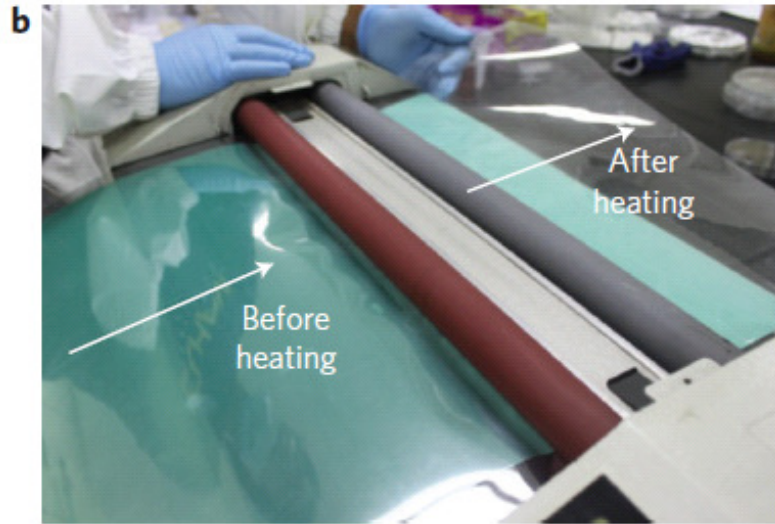
Nano Lett. 2011, 11, 1786–1791

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



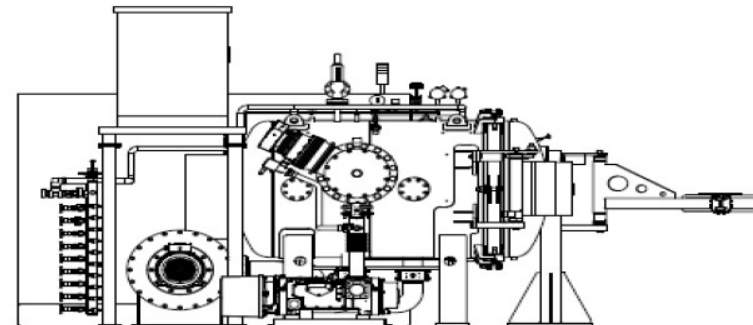
Small dimensions substrates



Wafers & foils < 6''



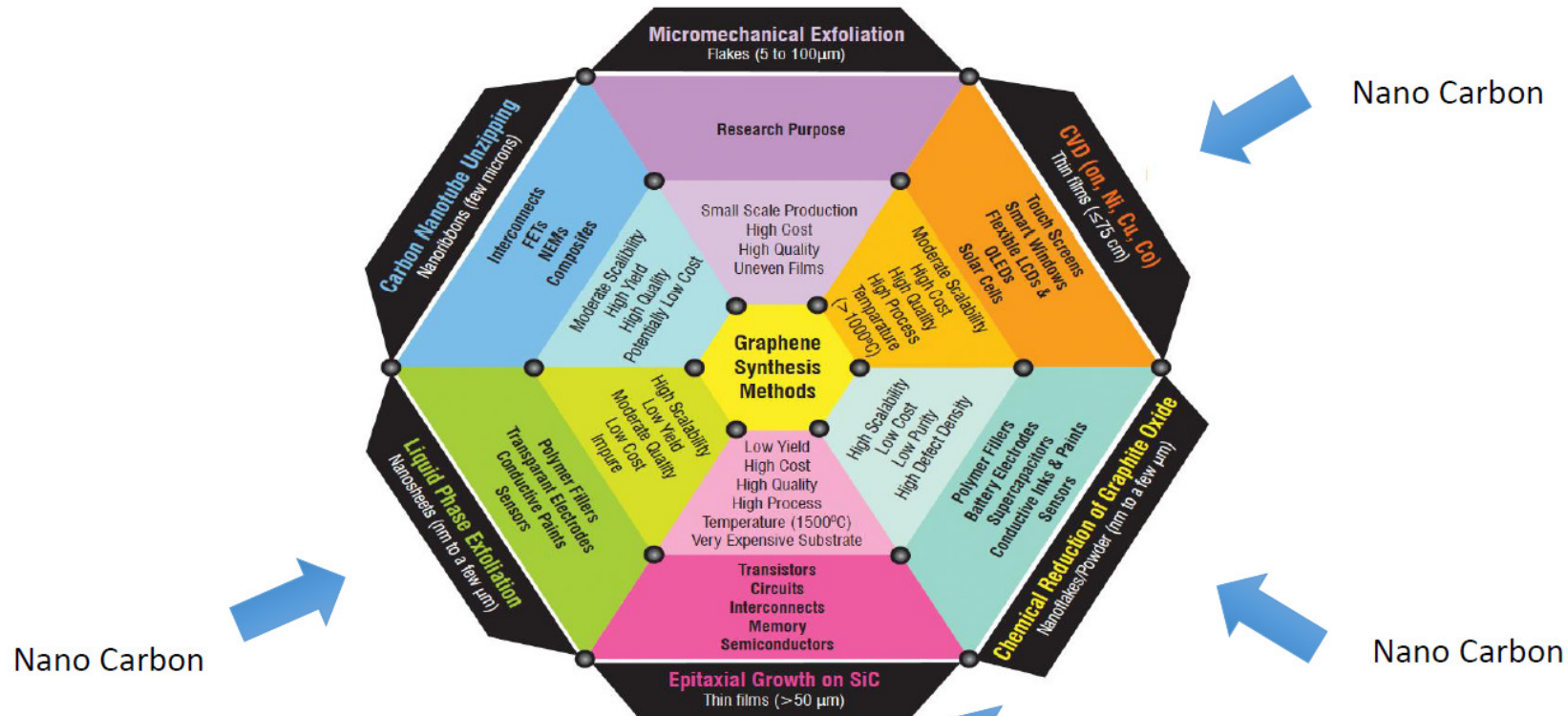
CVD 300mm x 300mm Cu foil
May 2014



CVD 500mm x 500mm Cu foil
installation 2014

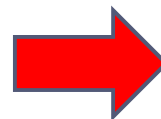
Źródło: ARP

Positioning of Nano-Carbon



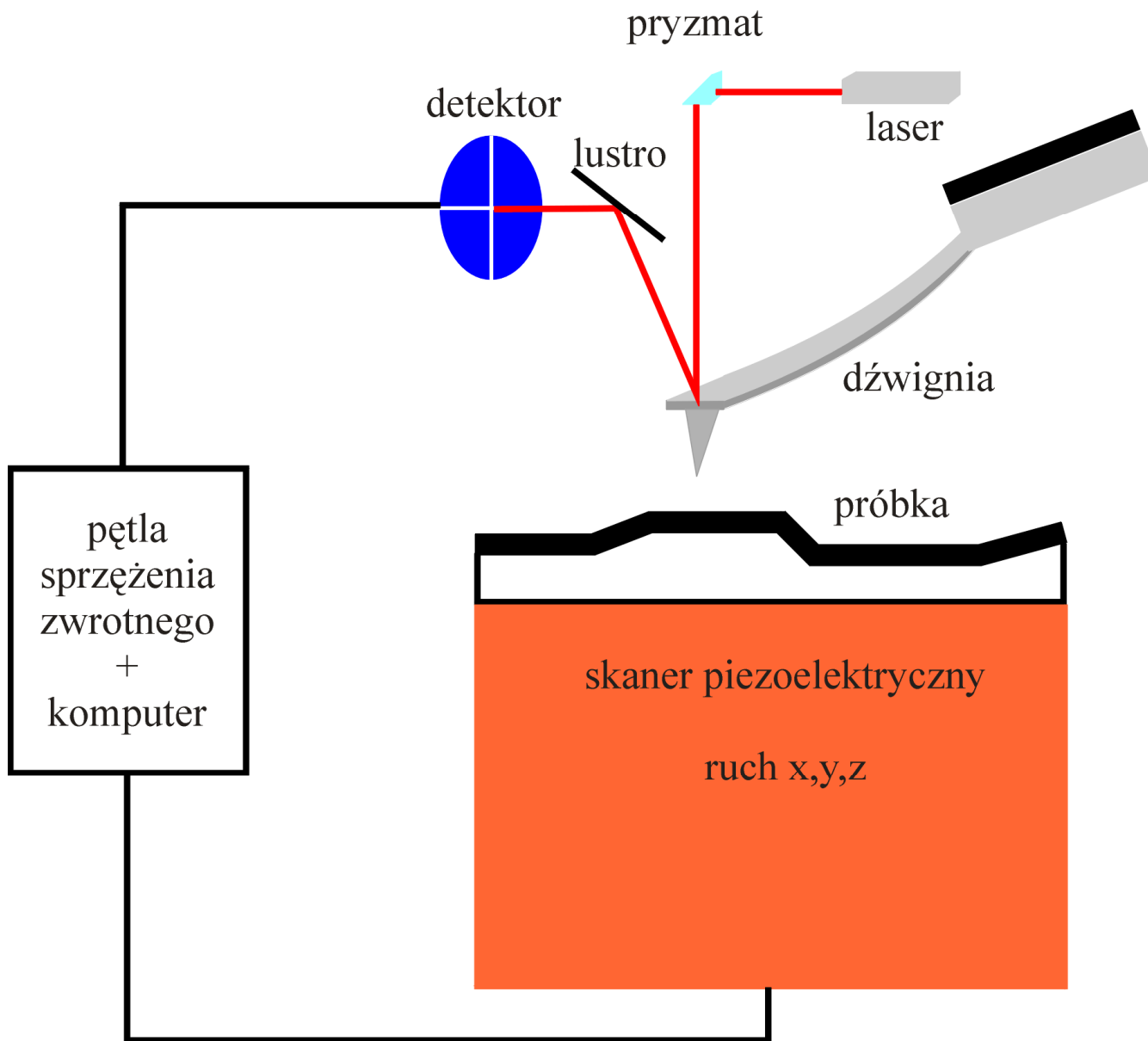
www.nano-carbon.pl www.grapheneshop.pl

Sprawdźmy co można kupić!



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

ZASADA DZIAŁANIA MIKROSKOPU SIŁ ATOMOWYCH

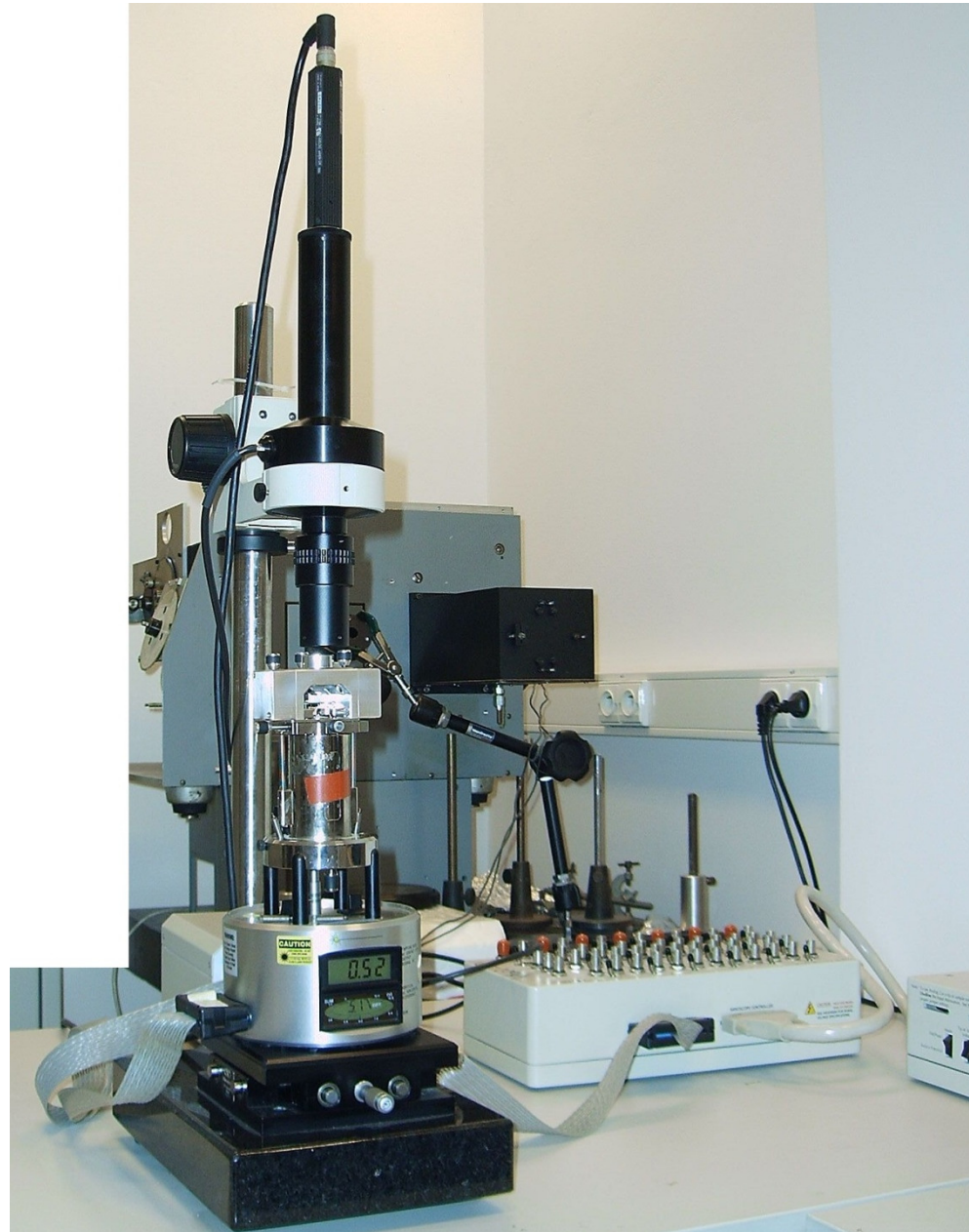


Mikroskop AFM

mikroskop
optyczny
z kamerą

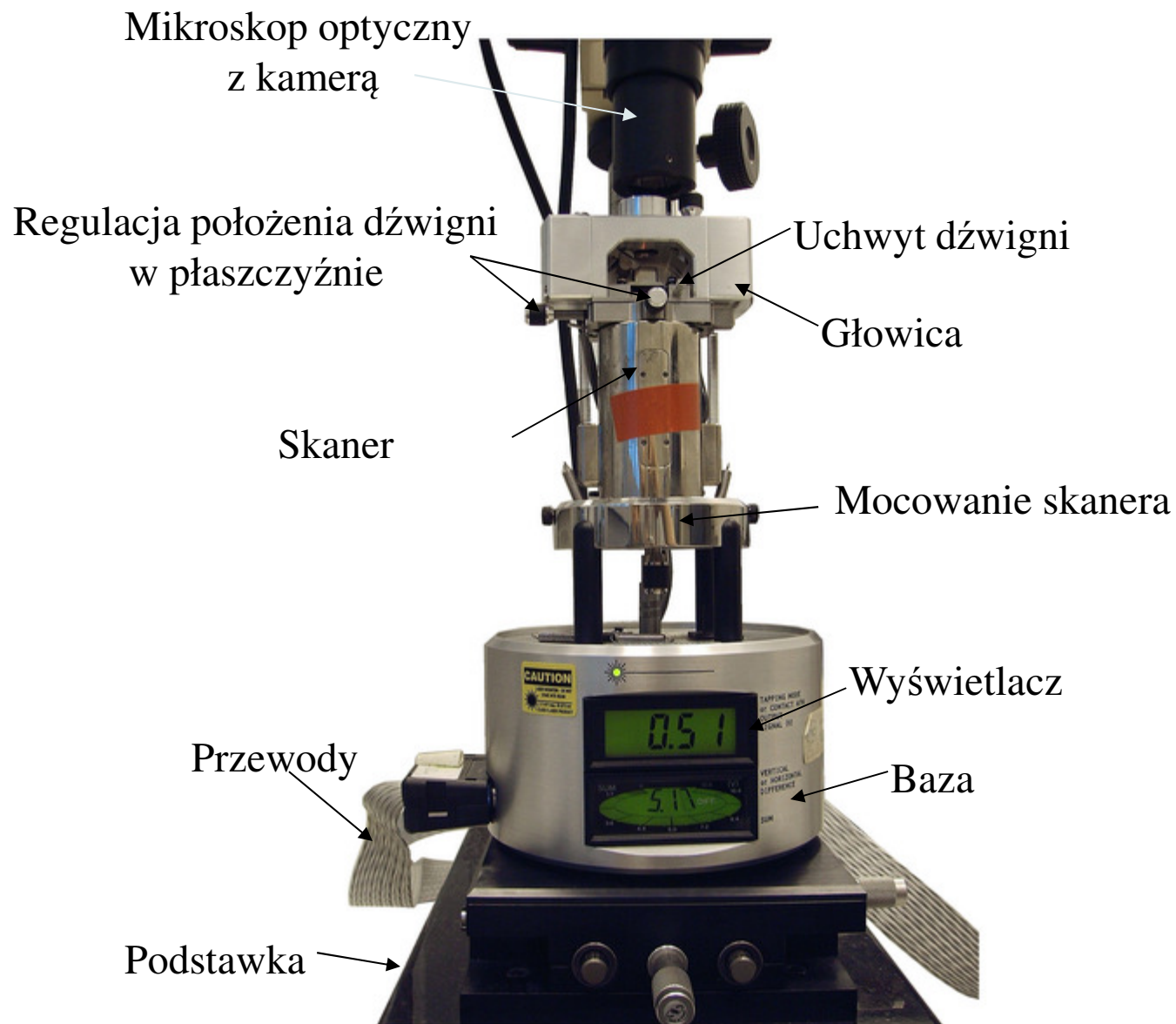
AFM
~25cm

podstawa

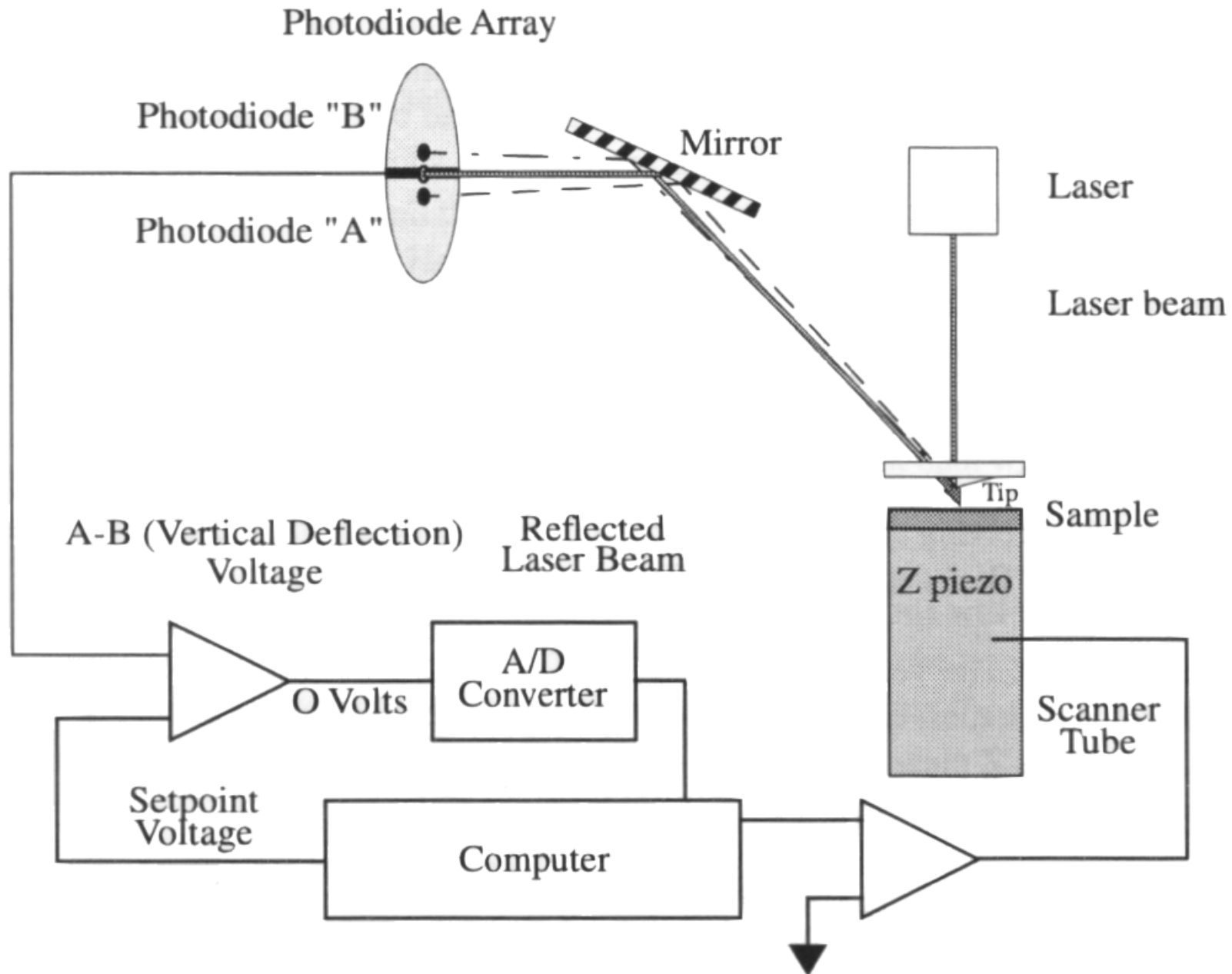


MultiMode AFM
+Nanoscope IIIa
Digital Instruments
(obecnie Veeco)

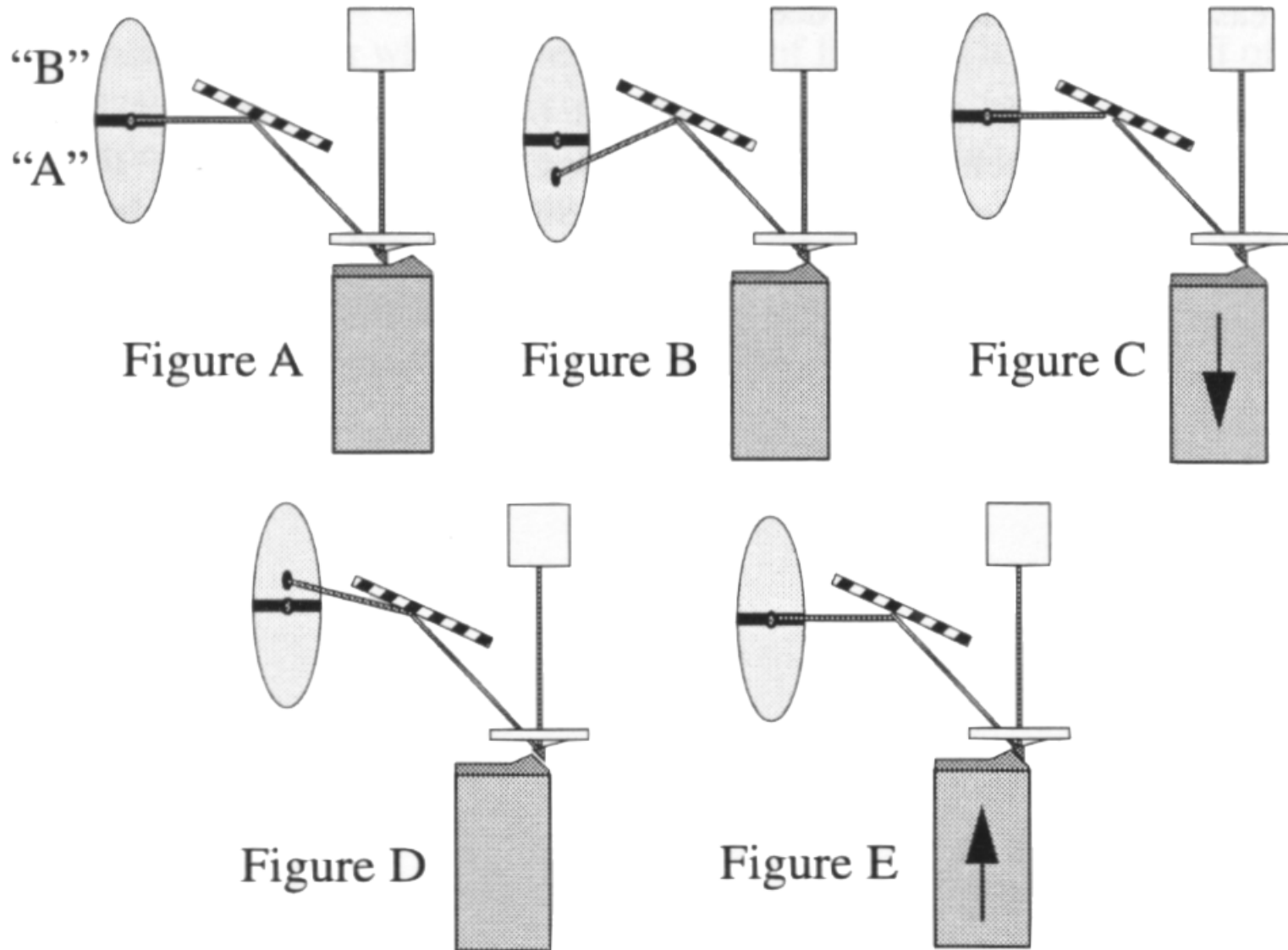
Budowa mikroskopu AFM: ruchoma próbka



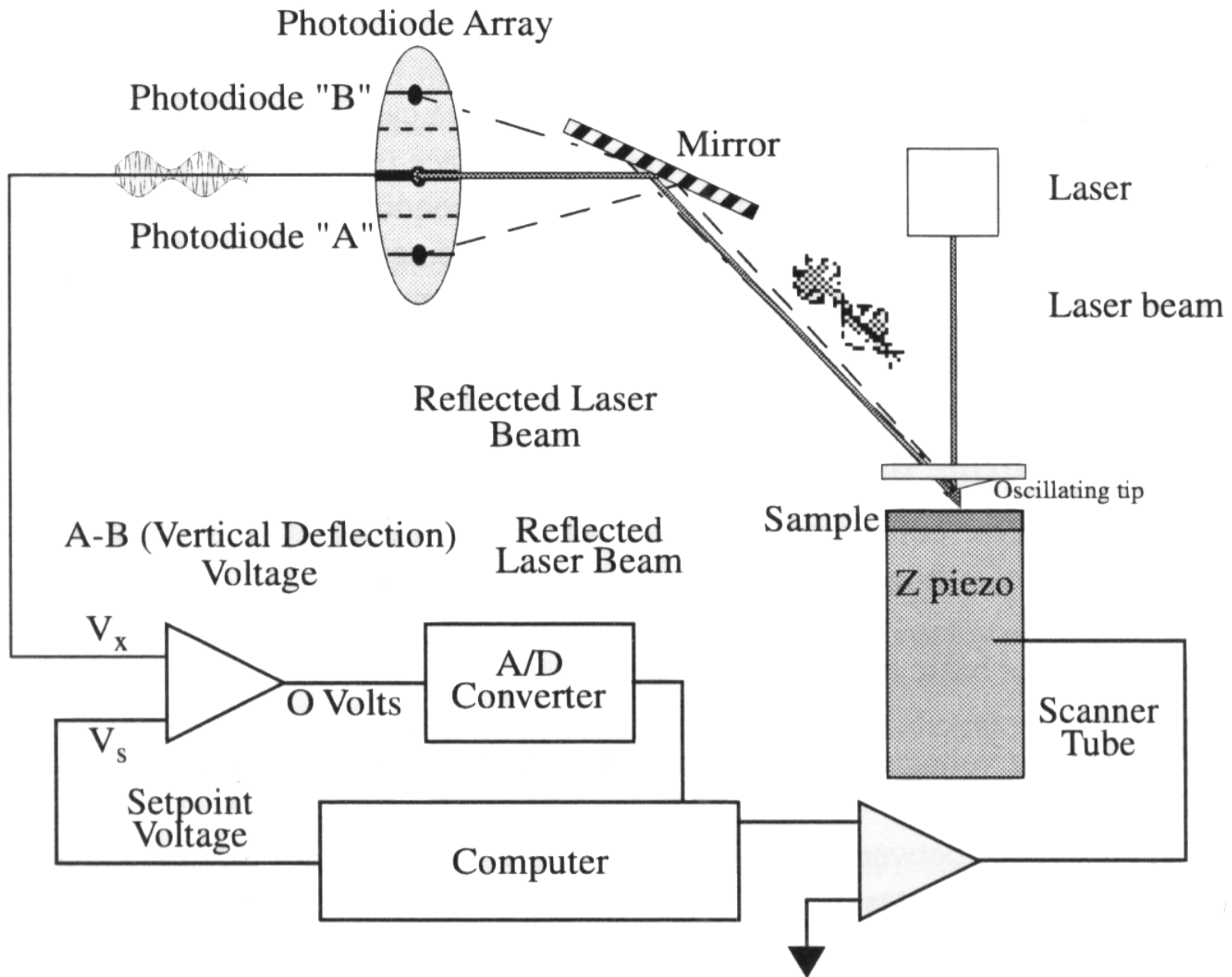
Tryb kontaktowy („contact mode“)



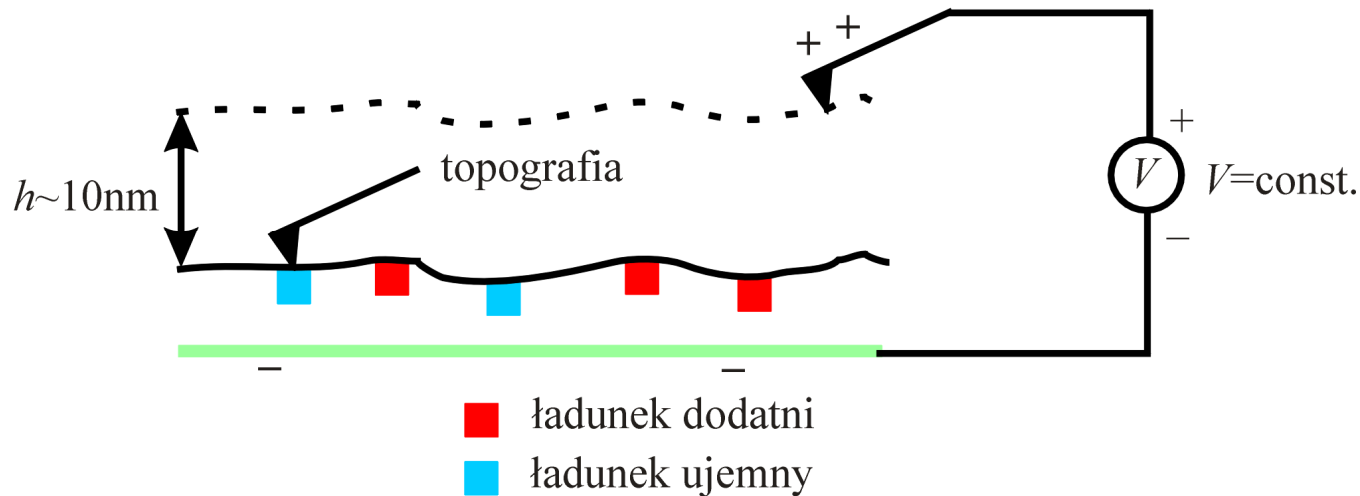
Tryb kontaktowy („contact mode”)



(TappingMode™ AFM)



EFM – Electric Force Microscopy (Kelvin Probe Microscopy)

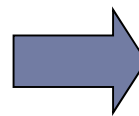


$$F(x) = F(x_0) + (x - x_0) \frac{\partial F}{\partial x} + \dots \quad \Delta\omega_0 = \frac{1}{2} \frac{\partial F}{\partial x} \frac{\omega_0}{k}$$

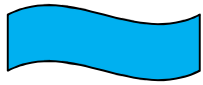
Siła elektryczna (gradient) \Leftrightarrow zmiana częstotliwości rezonansowej

Pętla sprzężenia zwrotnego: utrzymanie rezonansu

Przyciąganie \Leftrightarrow Spadek częstotliwości
Odpychanie \Leftrightarrow Wzrost częstotliwości

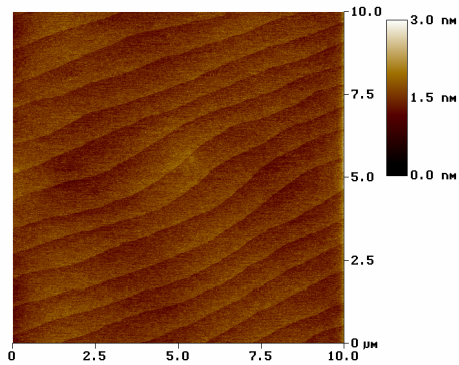


Doświadczenie w skali makro
z ciężarkiem na brzeszczocie
i magnesami...

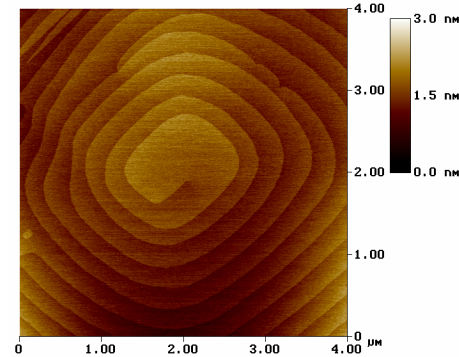


Wykład 12

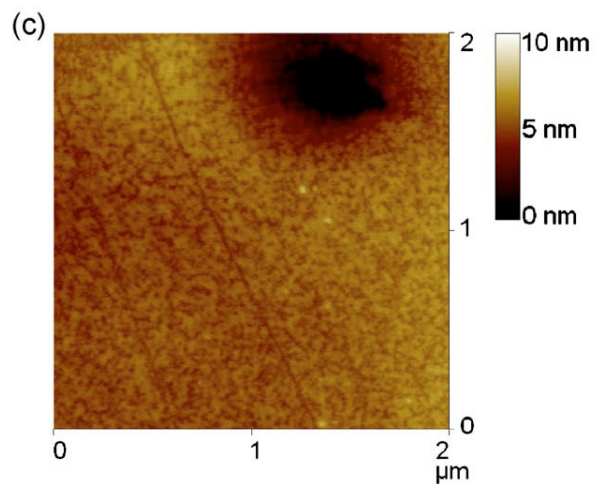
Mikroskop sił atomowych (AFM)



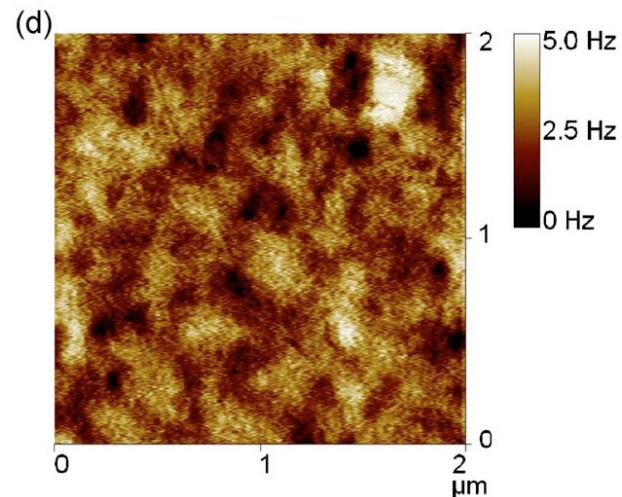
GaAs



Dyslokacja w InSb



AFM

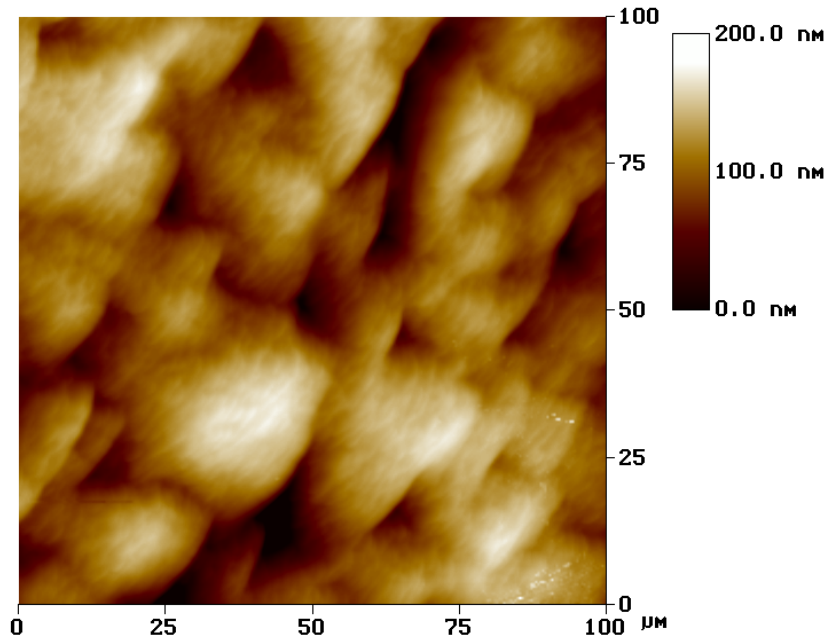


MFM

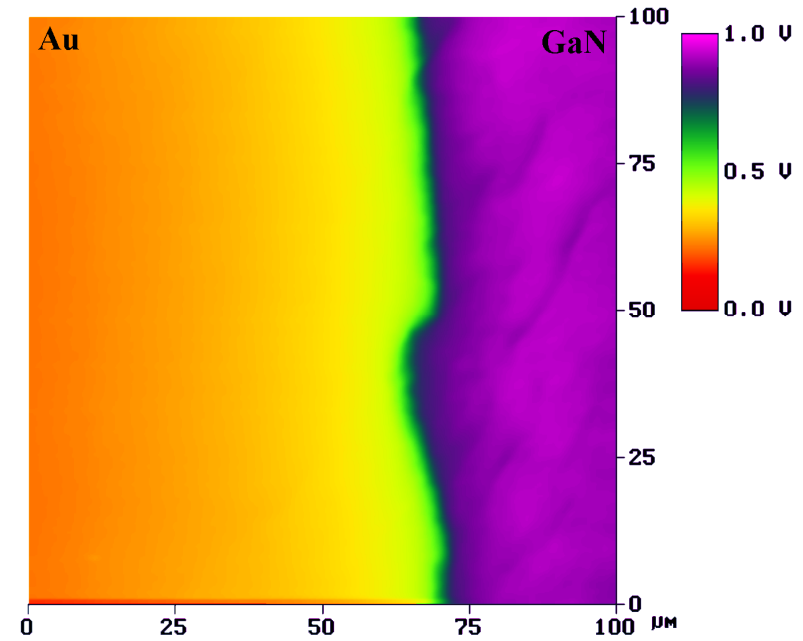
GaAs/(Ga,Mn)As

Dioda Schottky'ego Au/GaN

(złącze metal-półprzewodnik)



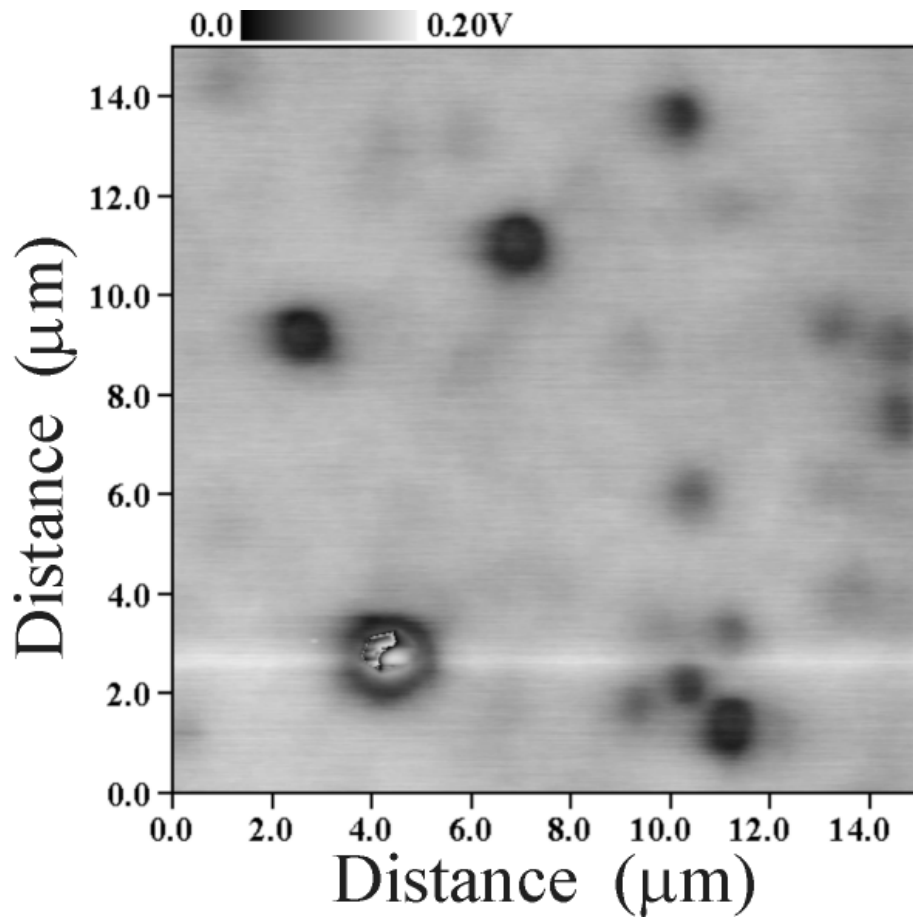
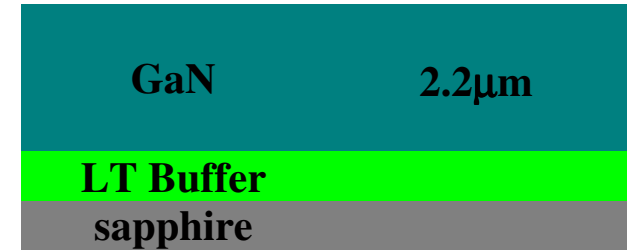
topografia



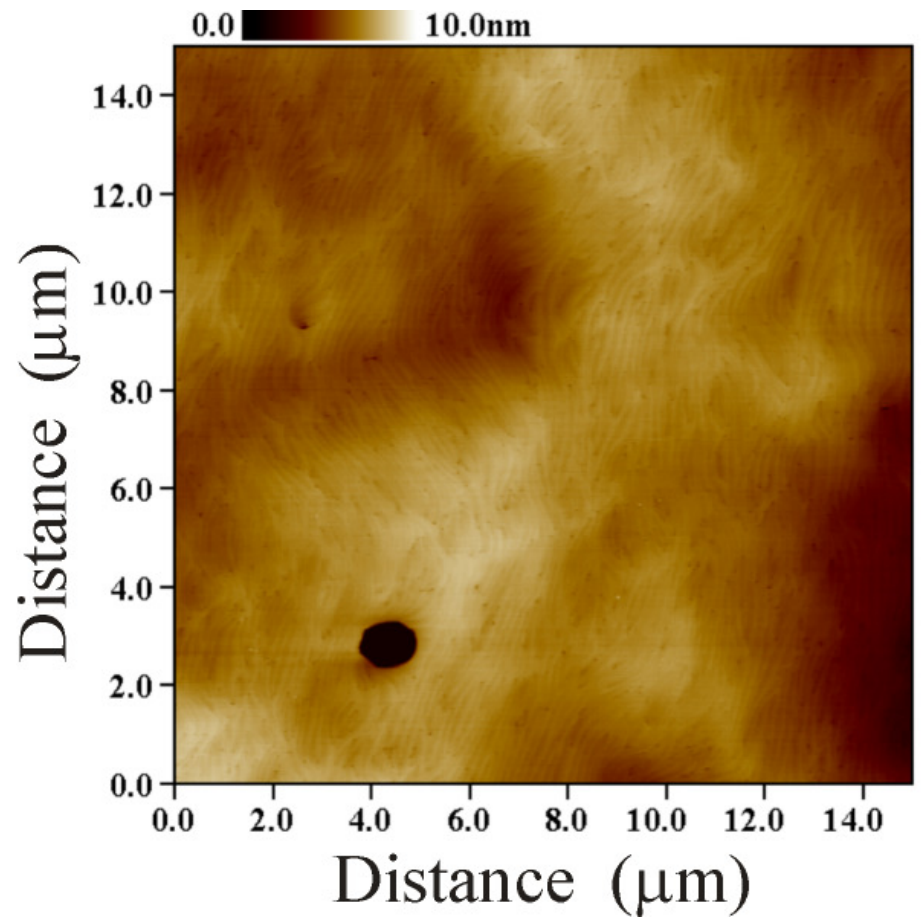
potencjał

granica półprzezroczystej warstwy Au

GaN



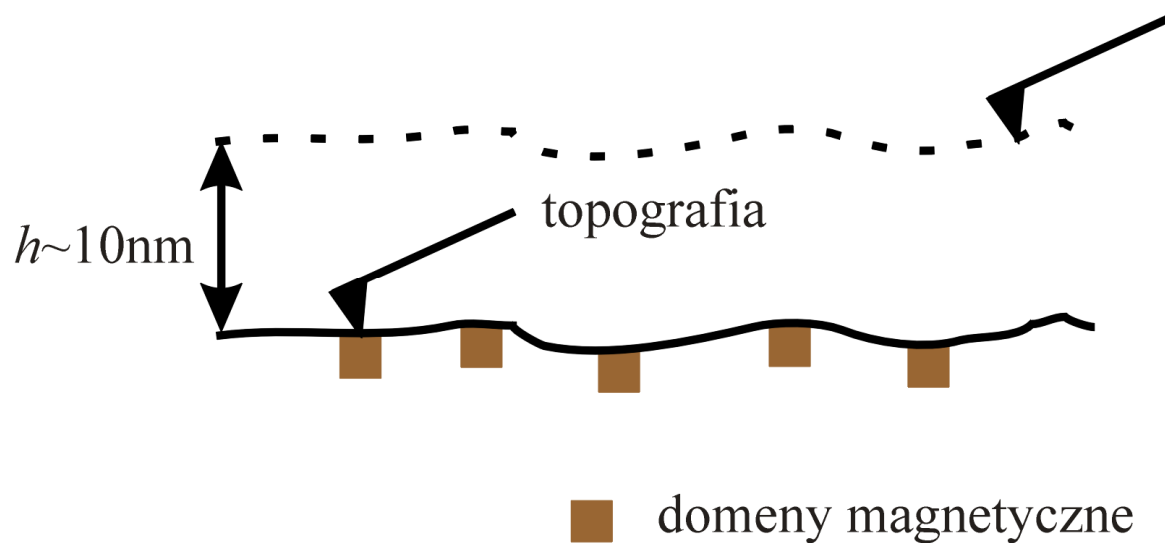
potencjał (KPFM)



topografia (AFM)

Rafał Bożek (Wydział Fizyki UW)

MFM – Magnetic Force Microscopy

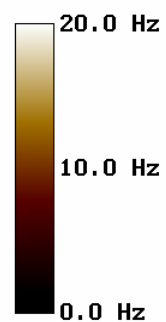
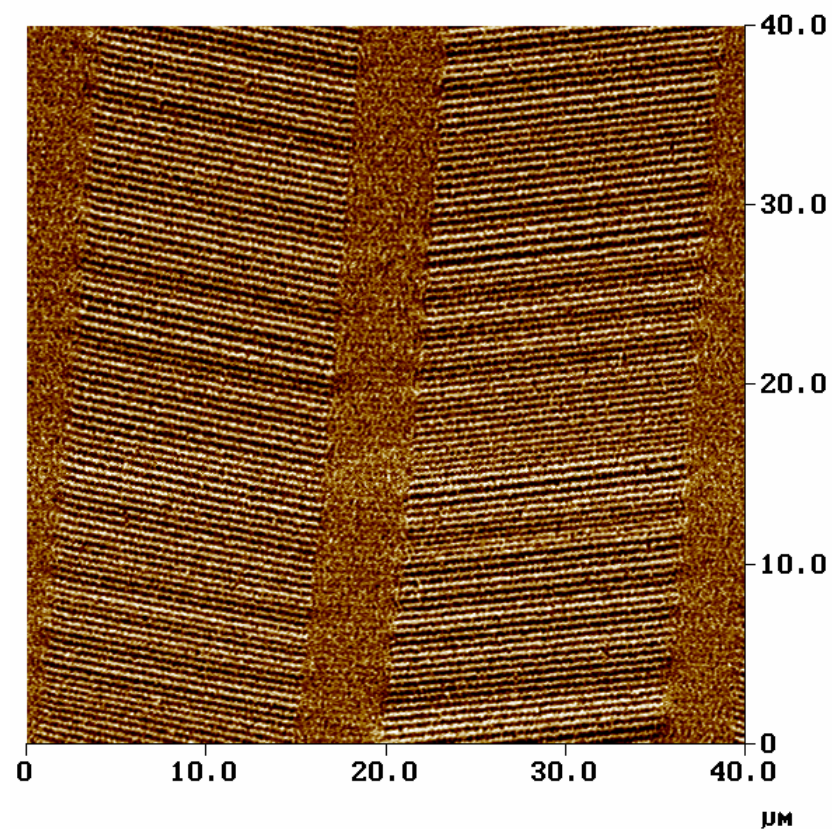
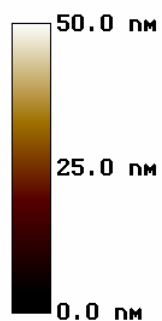
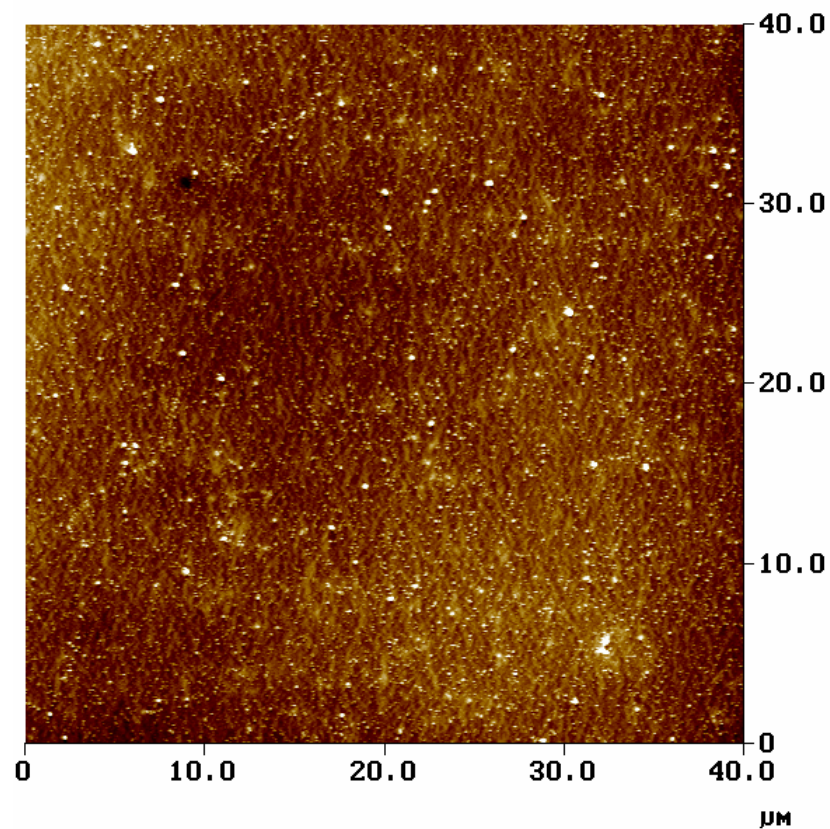


$$F(x) = F(x_0) + (x - x_0) \frac{\partial F}{\partial x} + \dots \quad \Delta\omega_0 = \frac{1}{2} \frac{\partial F}{\partial x} \frac{\omega_0}{k}$$

Siła magnetyczna (gradient) \Leftrightarrow zmiana częstości rezonansowej

Pętla sprzężenia zwrotnego: utrzymanie rezonansu

Mikroskop sił magnetycznych (MFM)



Rafał Bożek (Wydział Fizyki UW)

Nanorurki węglowe

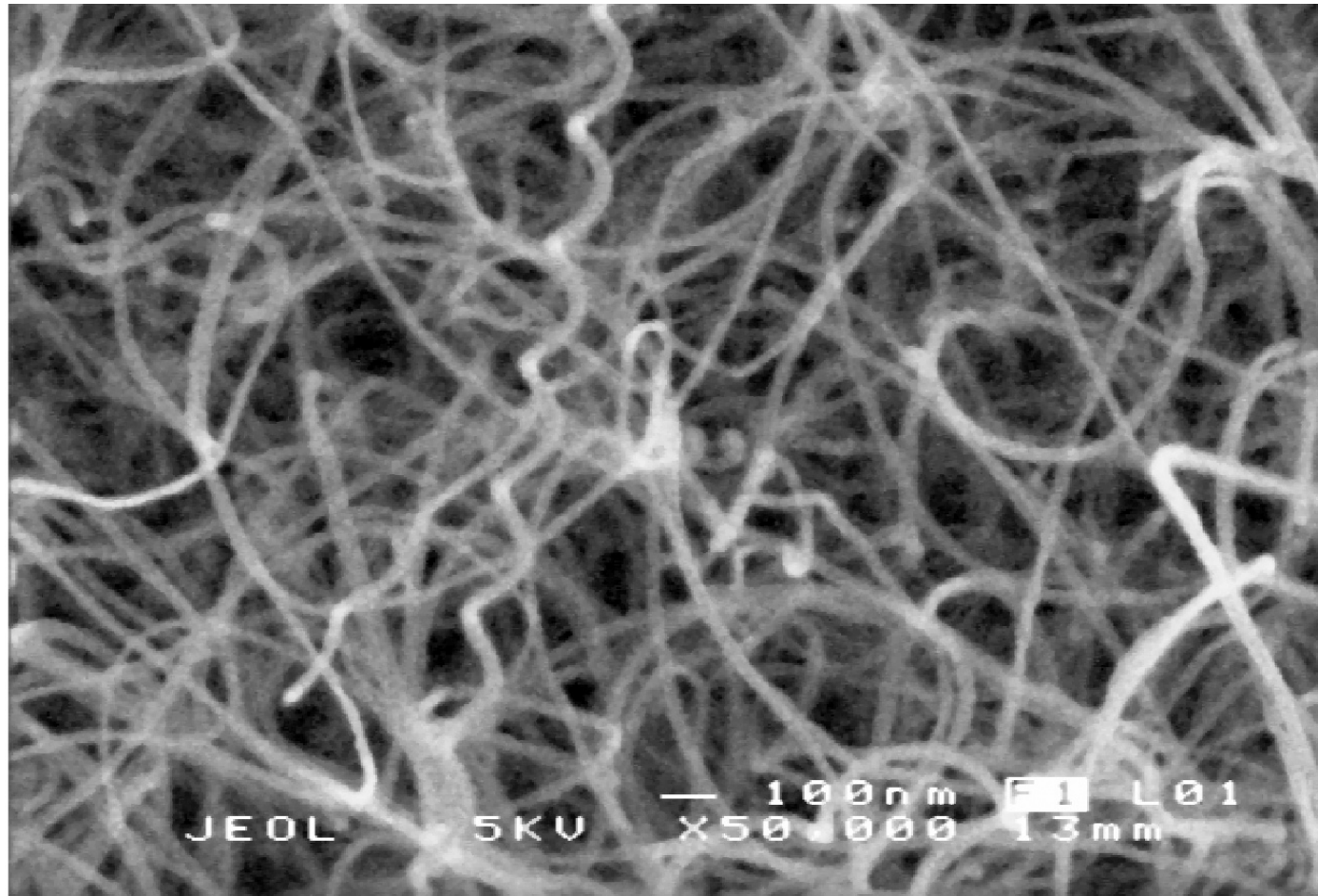
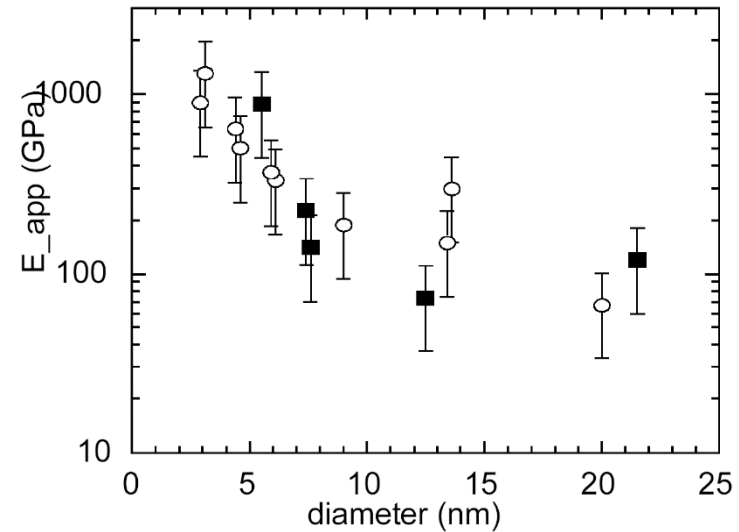
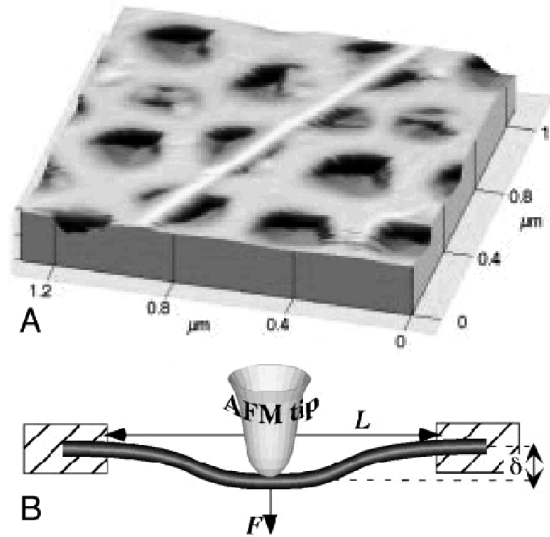


Figure 3. Scanning electron (SEM) micrographs of MWNT

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

Moduł Younga dla nanorurki?



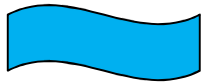
$$F = 10^{-12} - 10^{-8} \text{ N}$$

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 μm | 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 μm | nierówności < 10 μm |