



# Struktura i fizička svojstva niskodimenzionalnih sistema - nanotube

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# Sadržaj

- Niskodimenzionalni sistemi
- Ulaznica za nanosvet
- Čarolija ugljenika
- Simetrija
- Nanotube
- Primena
- Grafen



# Niskodimenzionalni sistemi

- Kristali koji nisu periodični duž tri nekolinearna pravca.
- Kvazi-dvodimenzionalni i kvazi-jednodimenzionalni sistemi.
- Zašto "licna" nije kvazi-jednodimenzionalan provodnik?



# Niskodimenzionalni sistemi

## 1-d sistemi

- Nanožice
- Nanotube
- Nanotrake
- Nano...

## 2-d sistemi

- Monoatomski slojevi
- Tanki slojevi
- Tanke heterostrukture
- 2-d elektronski sistem
- Vignerov kristal
- ...

- Kvantne tačke ("0-d")



# Niskodimenzionalni sistemi

- Tehnološki razvoj omogućio sveopštu minijaturizaciju.
- Pored male veličine čistoća uzoraka može da bude vrlo visoka.
- Pronalazak novih vrsta mikroskopa omogućio da vidimo vrlo male komadiće i da njima manipulišemo.

# Niskodimenzionalni sistemi

- Zašto su zanimljivi?
- Gotovo neslućene primene.
- Sjajni sistemi za proveravanje teorija (veza strukture i fizičkih svojstava).
- Nova fizika?
  - Topološki izolatori
  - Landau?
  - 2D elektronski gas
  - Dirakovi elektroni...



# Nova vrsta mikroskopa

SPM = Scanning Probe Microscopy



Gerd Binnig



Heinrich Rohrer

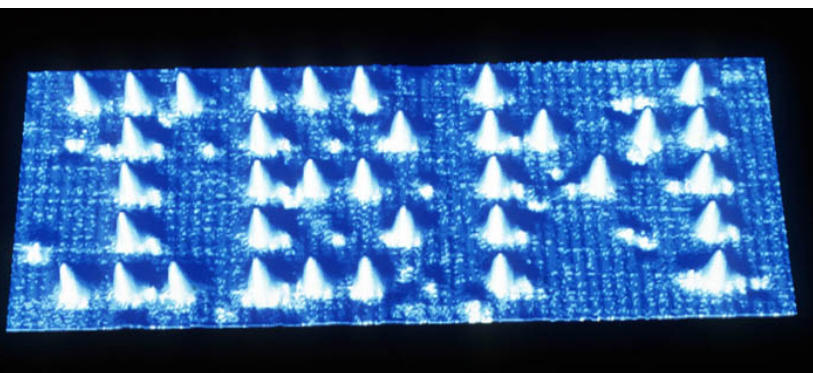
IBM Zürich Research Laboratory

$600 \text{ nm} = 6 \cdot 10^{-7} \text{ m} \approx 10^{-6} \text{ m}$

1986. Podelili polovinu Nobelove nagrade za fiziku.

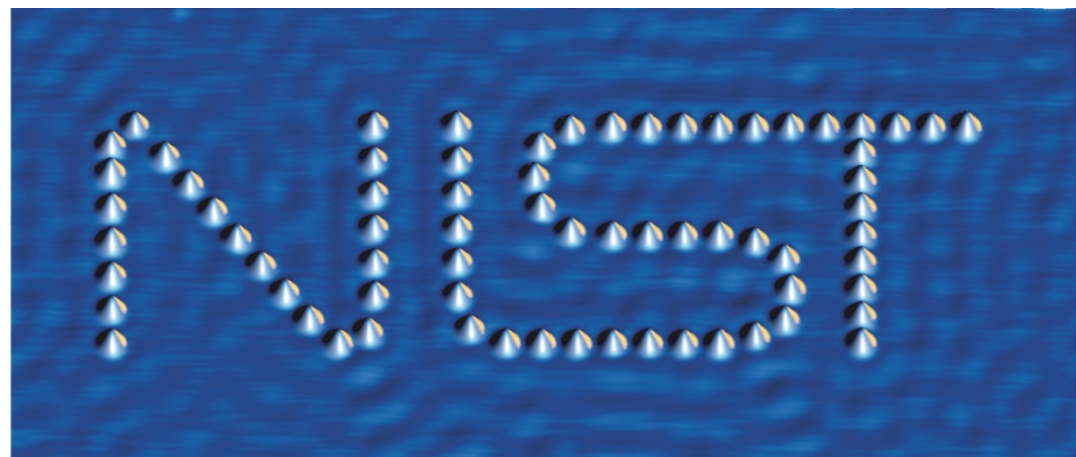


# Nova vrsta mikroskopa



Logo IBM-a napisan sa 35 atoma ksenona na bakarnoj podlozi, 1989.

Logo širine 40 nanometara  
Napravljen atomima kobalta na bakarnoj površini. Neravnine u pozadini su talasi elektrona. 2004.

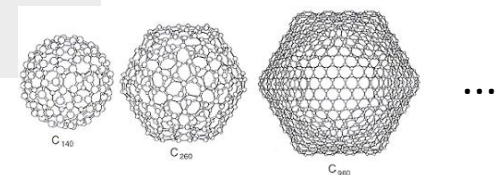
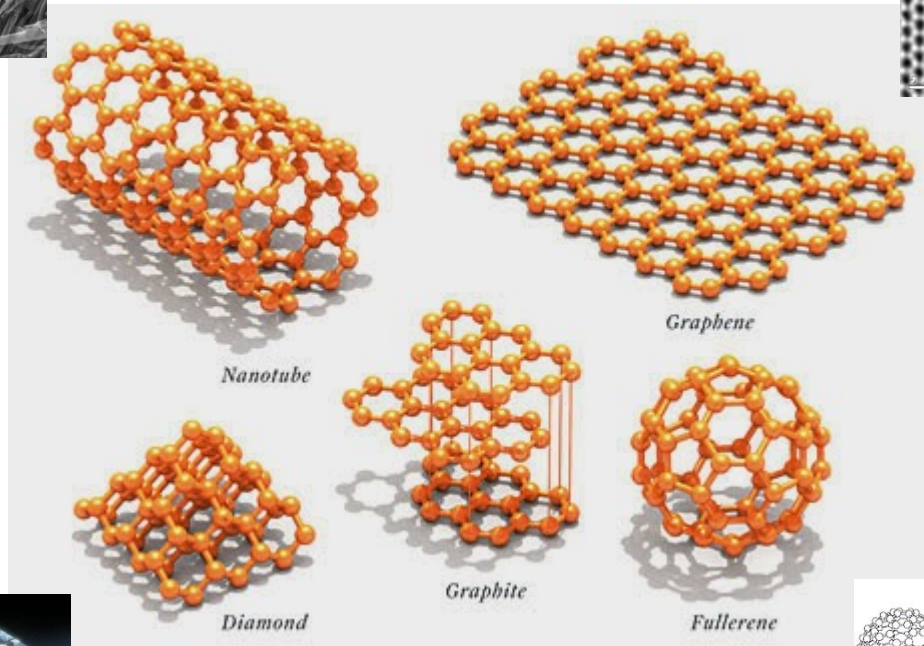
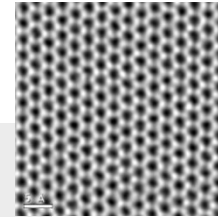
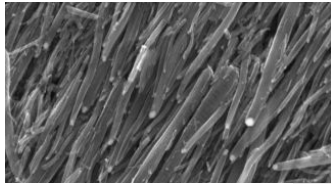


*National Institute of Standards and Technology*

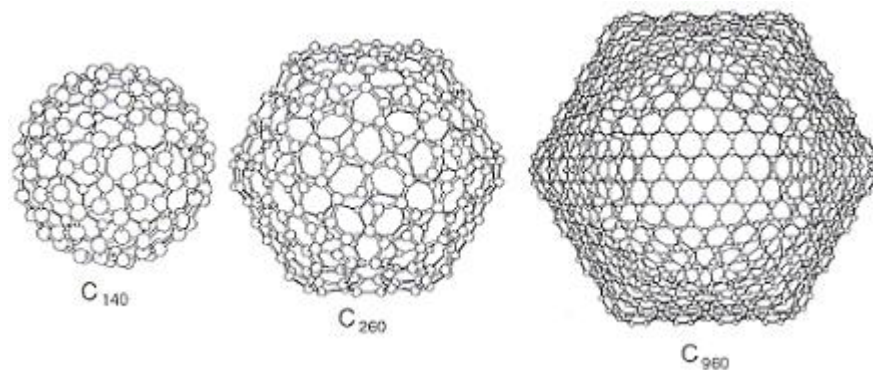
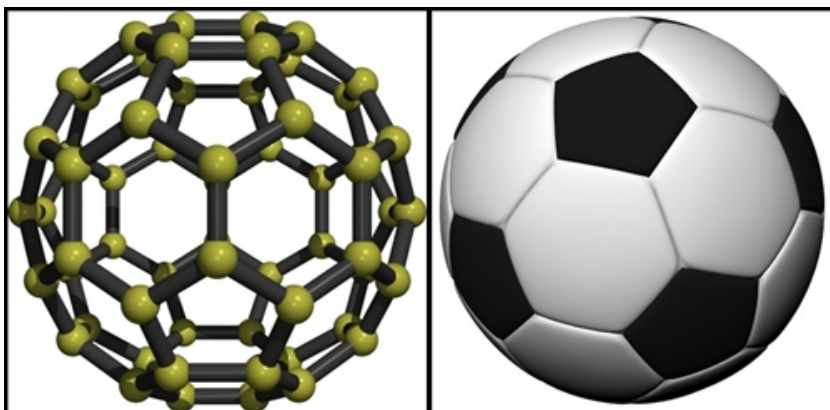




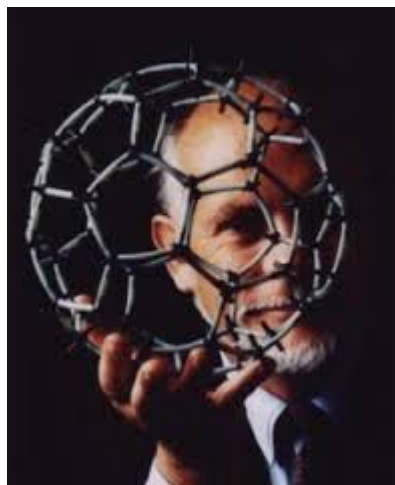
# Čarolija ugljenika



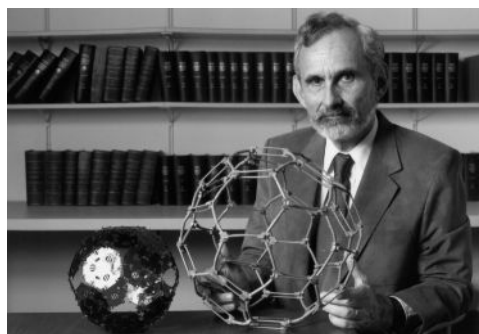
# Čarolija ugljenika: počeci



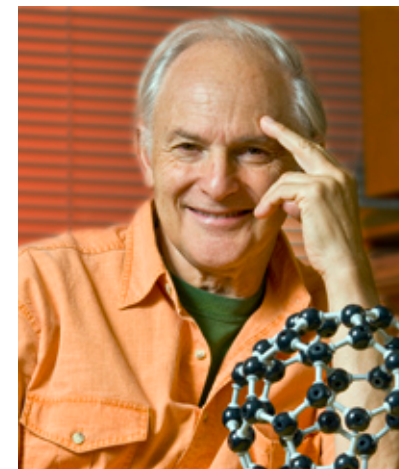
1996. NN



Ričard Smoli



Robert Kerl



Harold Kroto

# Čarolija ugljenika: počeci

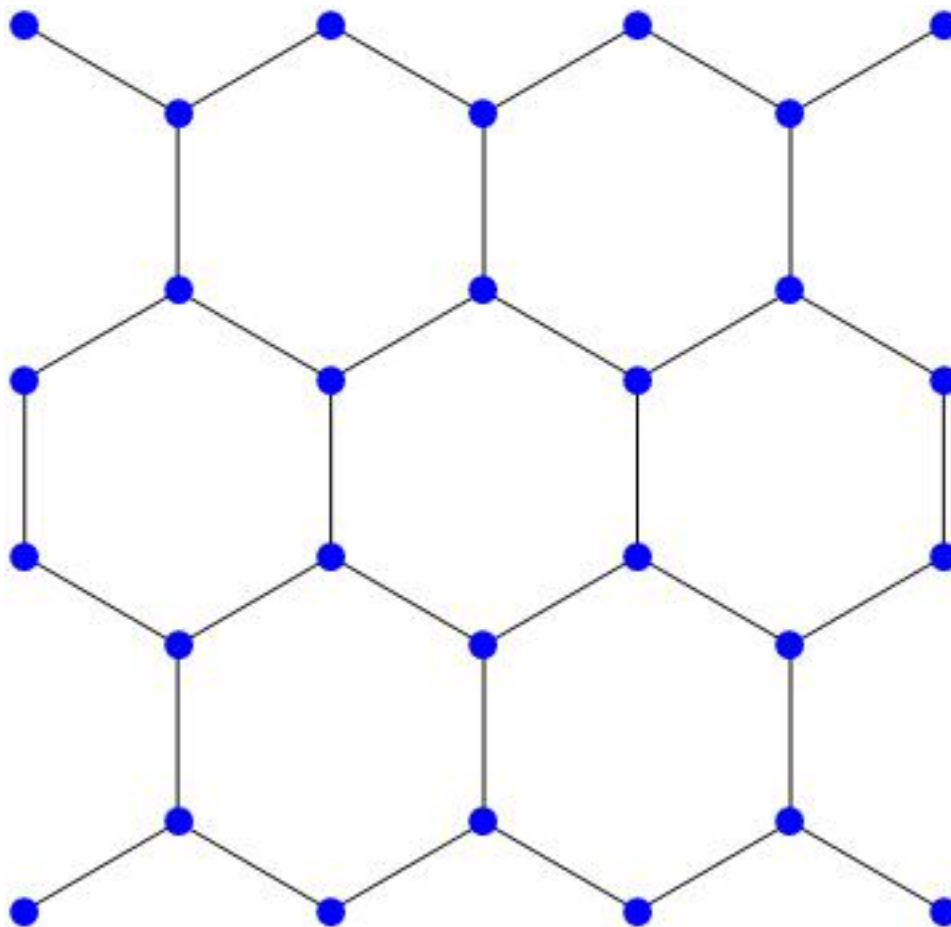


Ričard Bakminster Fuller

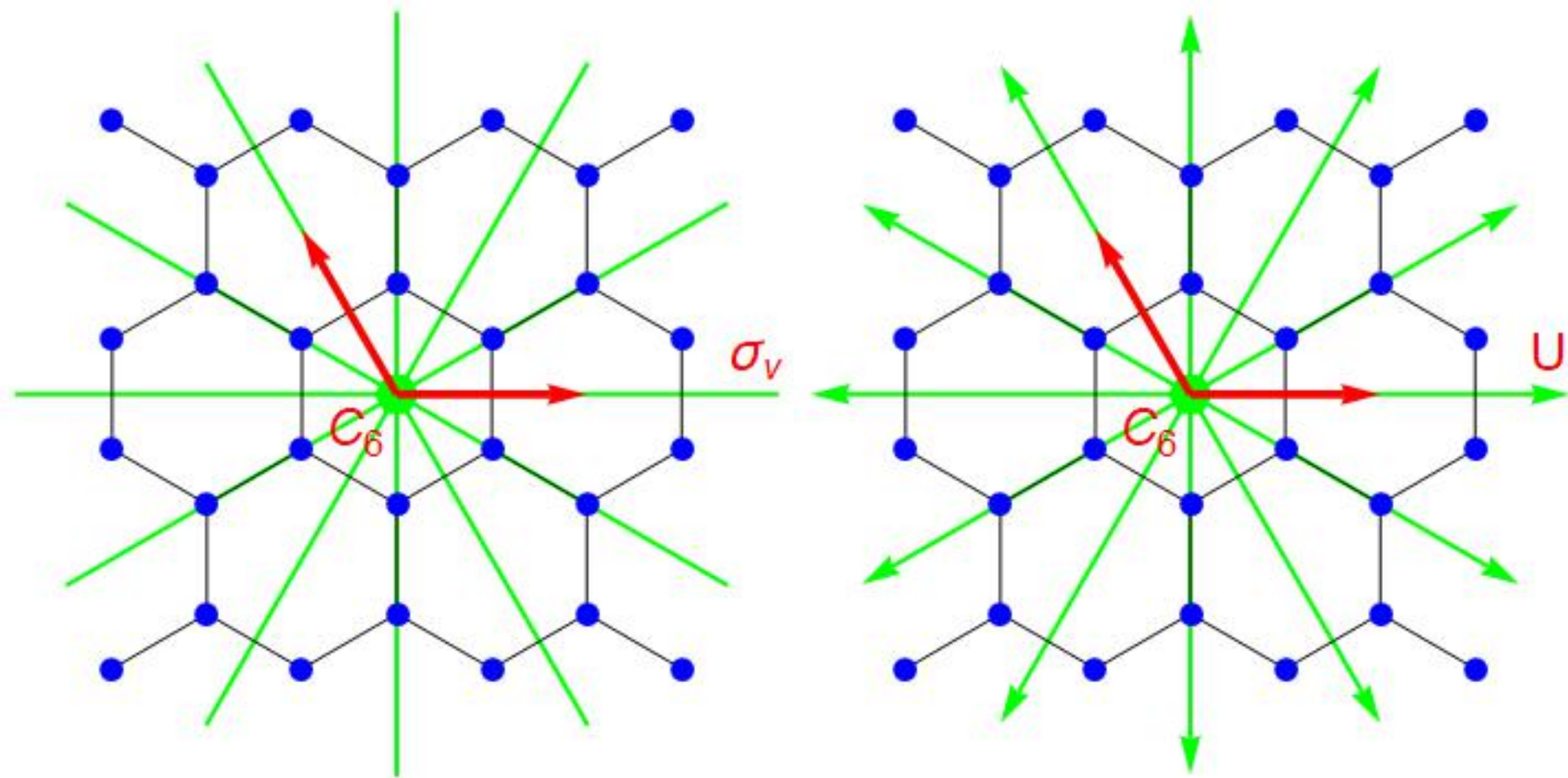
# Simetrija



# Simetrija

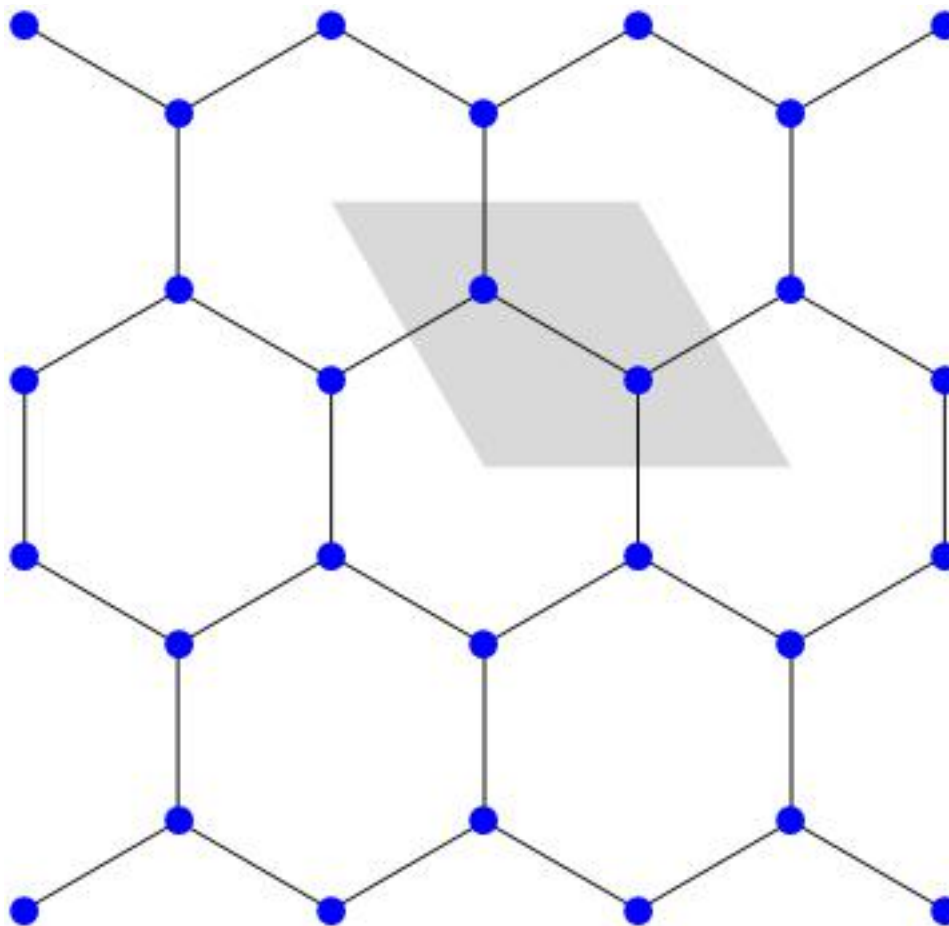


# Simetrija

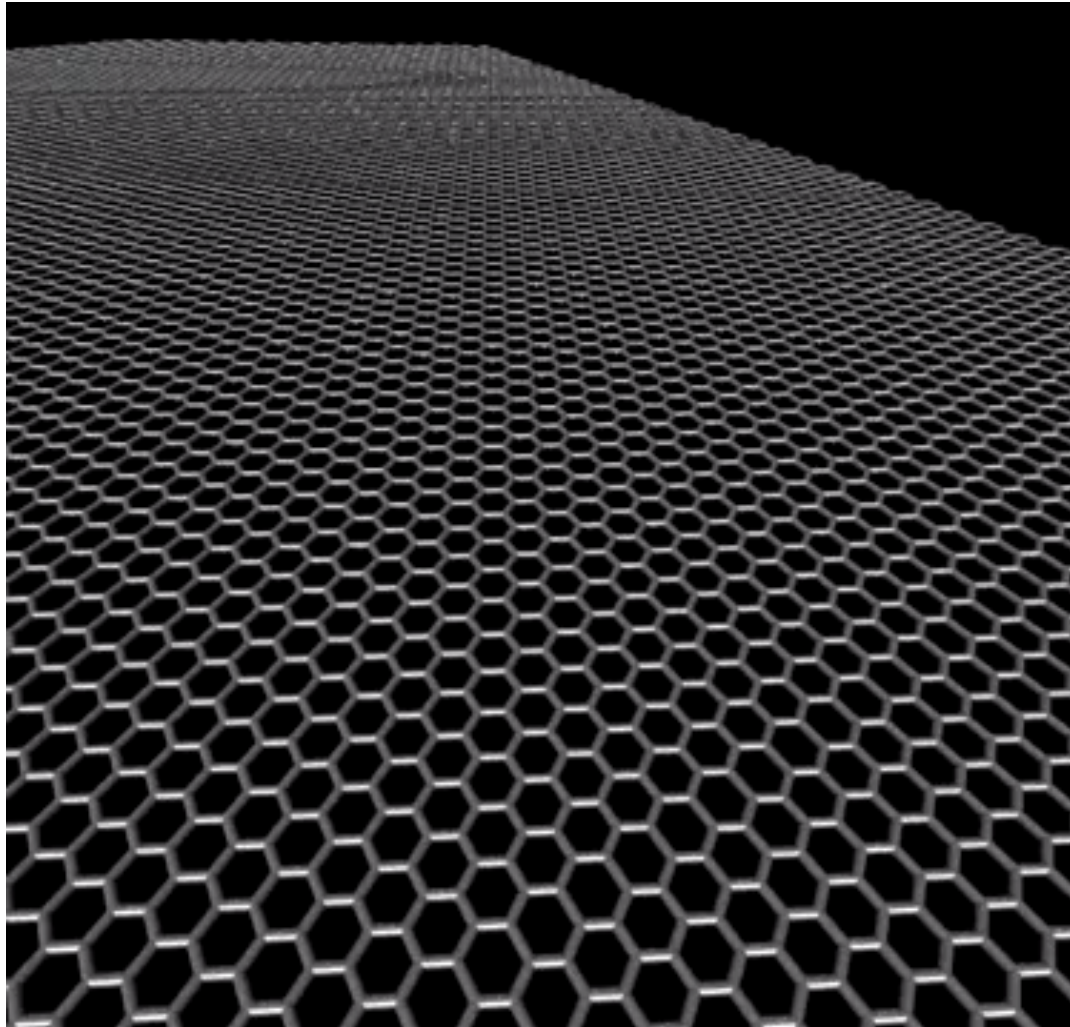


$TD_{6h}$

# Simetrija



# Nanotube





# Nanotube: otkriće



Sumio Iijima (1991)

1952

ЖУРНАЛ ФИЗИЧЕСКОЙ ХИМИИ т. XXVI, вып. 1

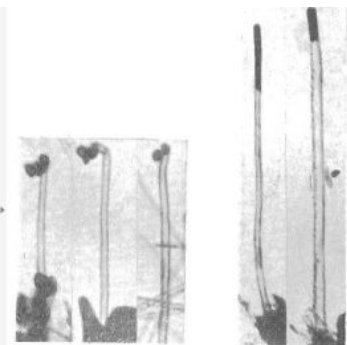


Рис. 7  
× 20.000

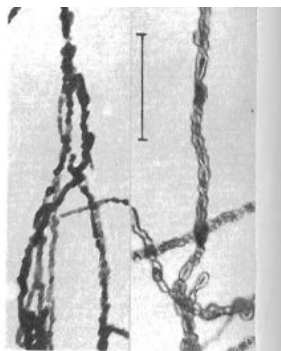


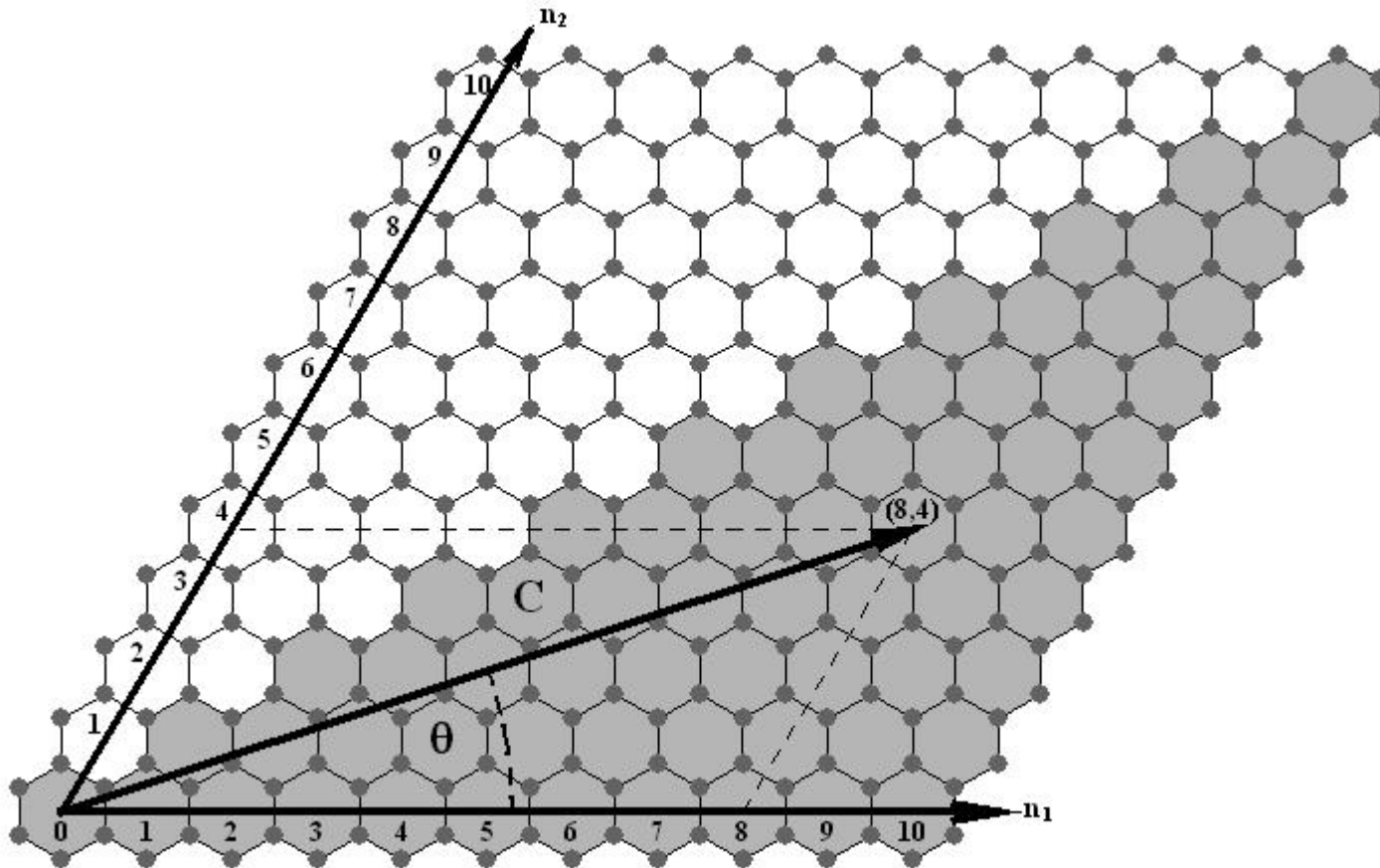
Рис. 8

**О СТРУКТУРЕ УГЛЕРОДА, ОБРАЗУЮЩЕГОСЯ ПРИ  
ТЕРМИЧЕСКОМ РАЗЛОЖЕНИИ ОКИСИ УГЛЕРОДА  
НА ЖЕЛЕЗНОМ КОНТАКТЕ**

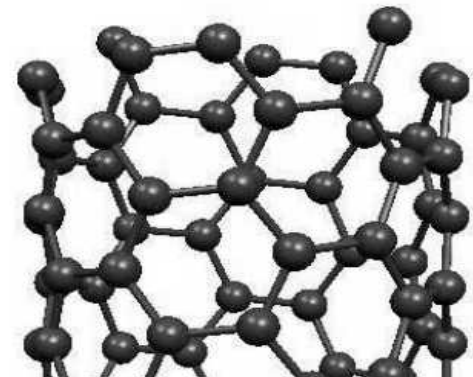
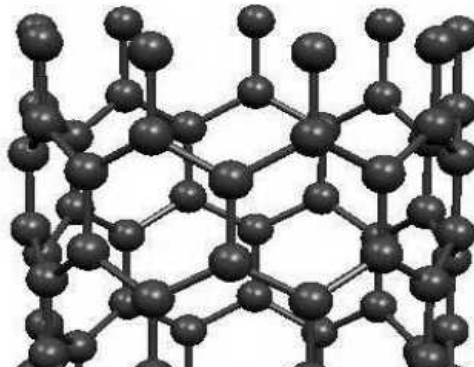
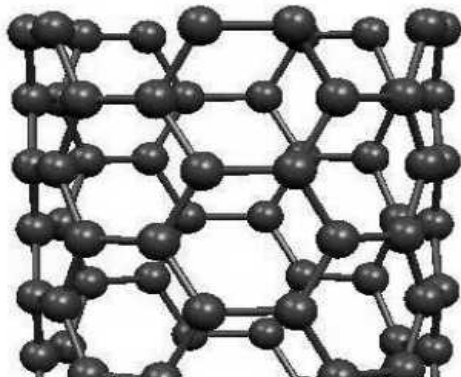
*Л. В. Радуйкевич и В. М. Лукьянович*

...ная работа возникла в связи с электронно-микроскопическим из-  
...м структуры различных адсорбентов, главным образом активных  
...графита и т. п. При исследовании препаратов углерода мы обратили  
...внимание на сажу, получающуюся при разложении окиси углерода на же-

# Nanotube



# Vrste ugljeničnih nanotuba

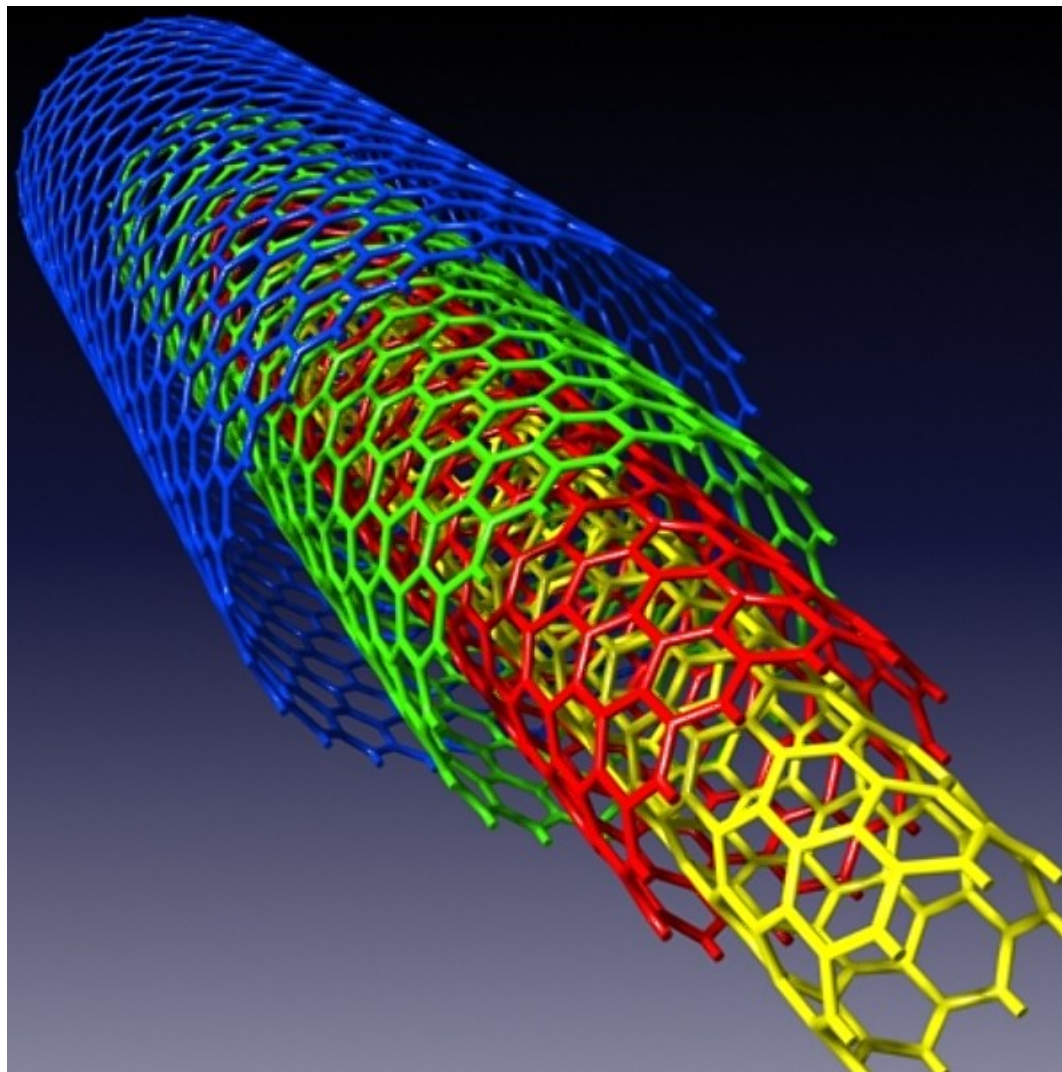


Sedlasta tuba  
( $n,n$ )

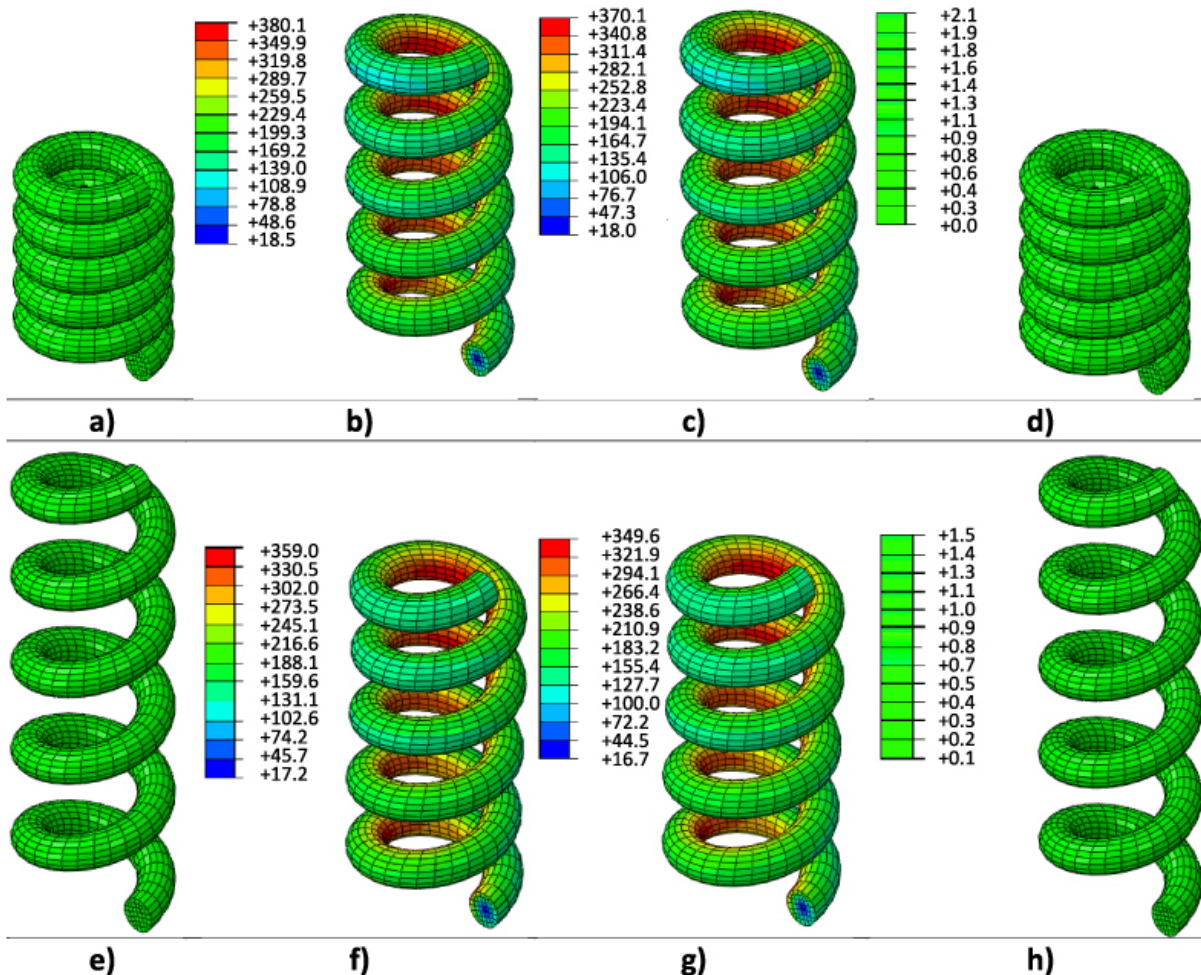
Cik-cak tuba  
( $n,0$ )

Kiralna tuba  
( $n,m$ )

# Vrste ugljeničnih nanotuba



# Vrste ugljeničnih nanotuba



# Primena simetrije: teorijski model

- Simetrija i relaksirana konfiguracija

*Damnjanović et al. PRB 60 (4) (1999) 2728;*

*Lazić et al., J. Phys.: Condens. Matter 24 (48) (2012) 485302*

- Fononski spektar (FCM)

*Mohr et al., PRB 76 (3) (2007) 0354391*

- Elektronski spektar (DFTB)

*Milošević et al., PRB 67 (16) (2003) 165418*

- Absorpcioni spektar (+dipolna aproksimacija)

*Milošević et al. PRB 69 (2004) 113408*

- Ramanov spektar (+deformacioni potencijal)

*Nikolić, J. Phys.: Condens. Matter 22 (9) (2010) 095302.*

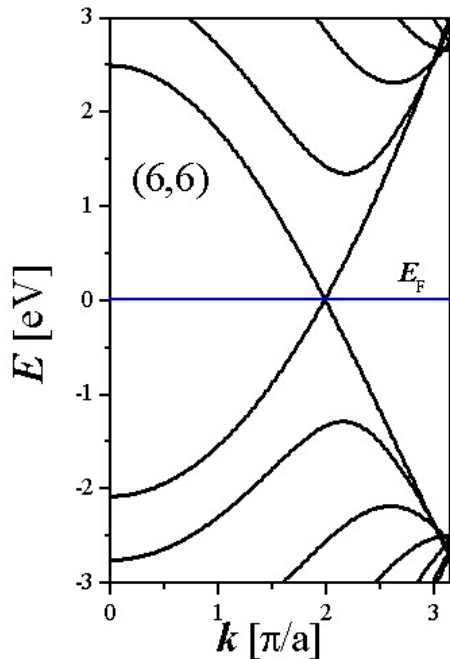
- Homogene deformacije

*Dmitrović et al., J. Phys.: Condens. Matter 25 (14) (2013) 145301*

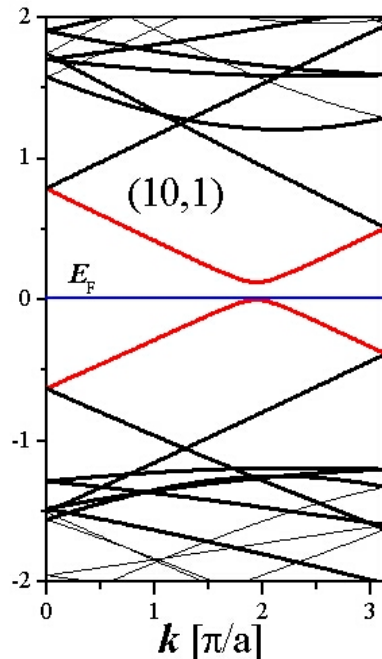
*Nikolić et al. J. Phys. Chem. C (2014) 118, 20576–20584.*



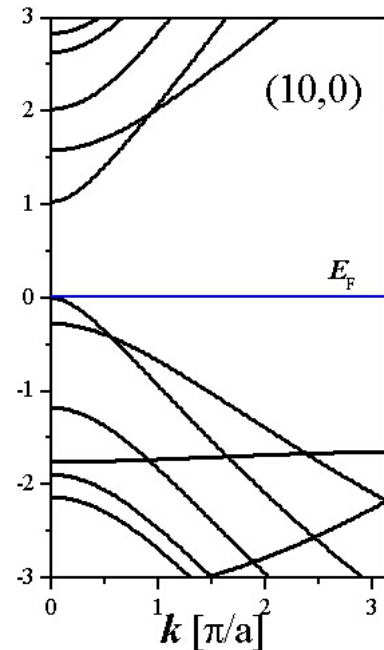
# Provodna svojstva



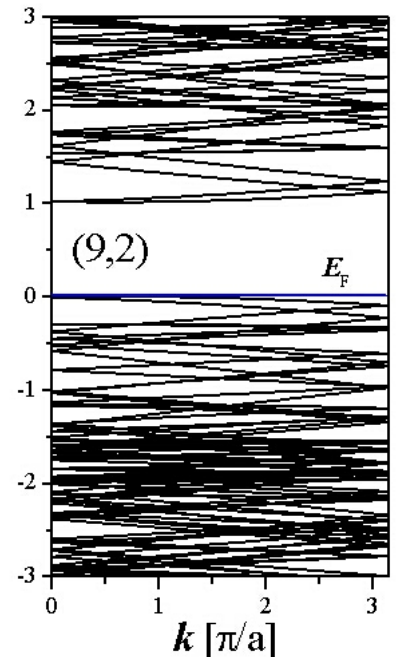
(n,n)  
metalne



(n,m) mod 3 = 0  
semimetalne



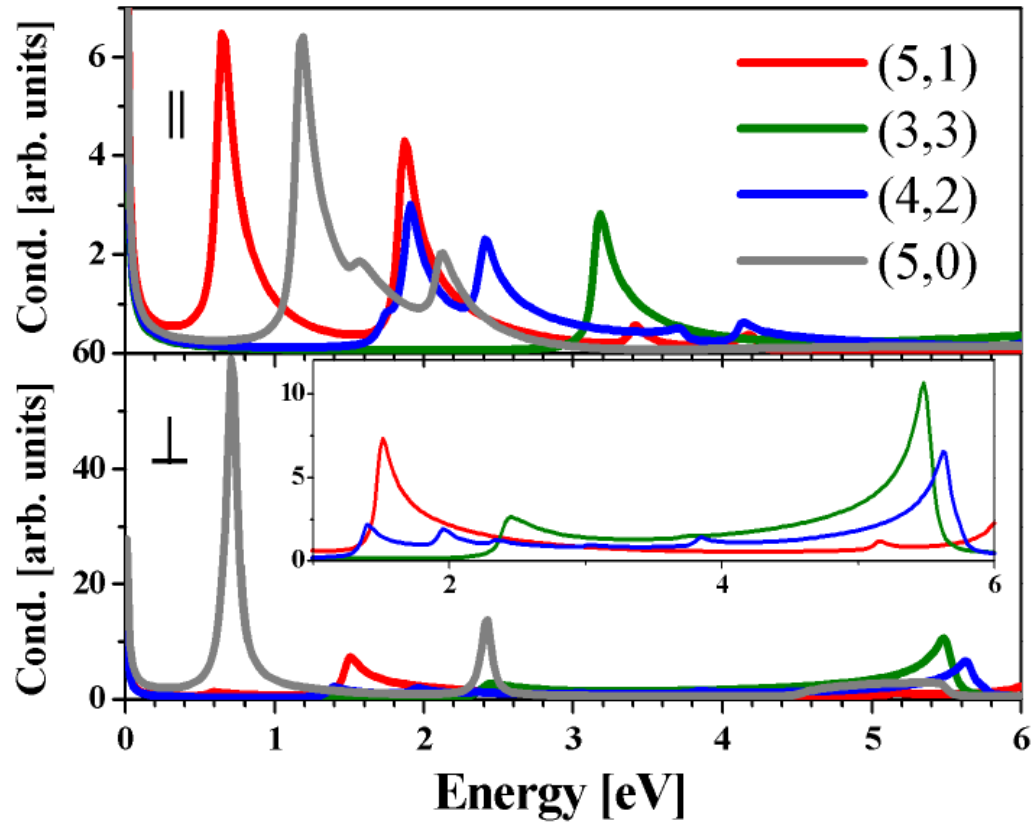
(n,0)



(n,m)

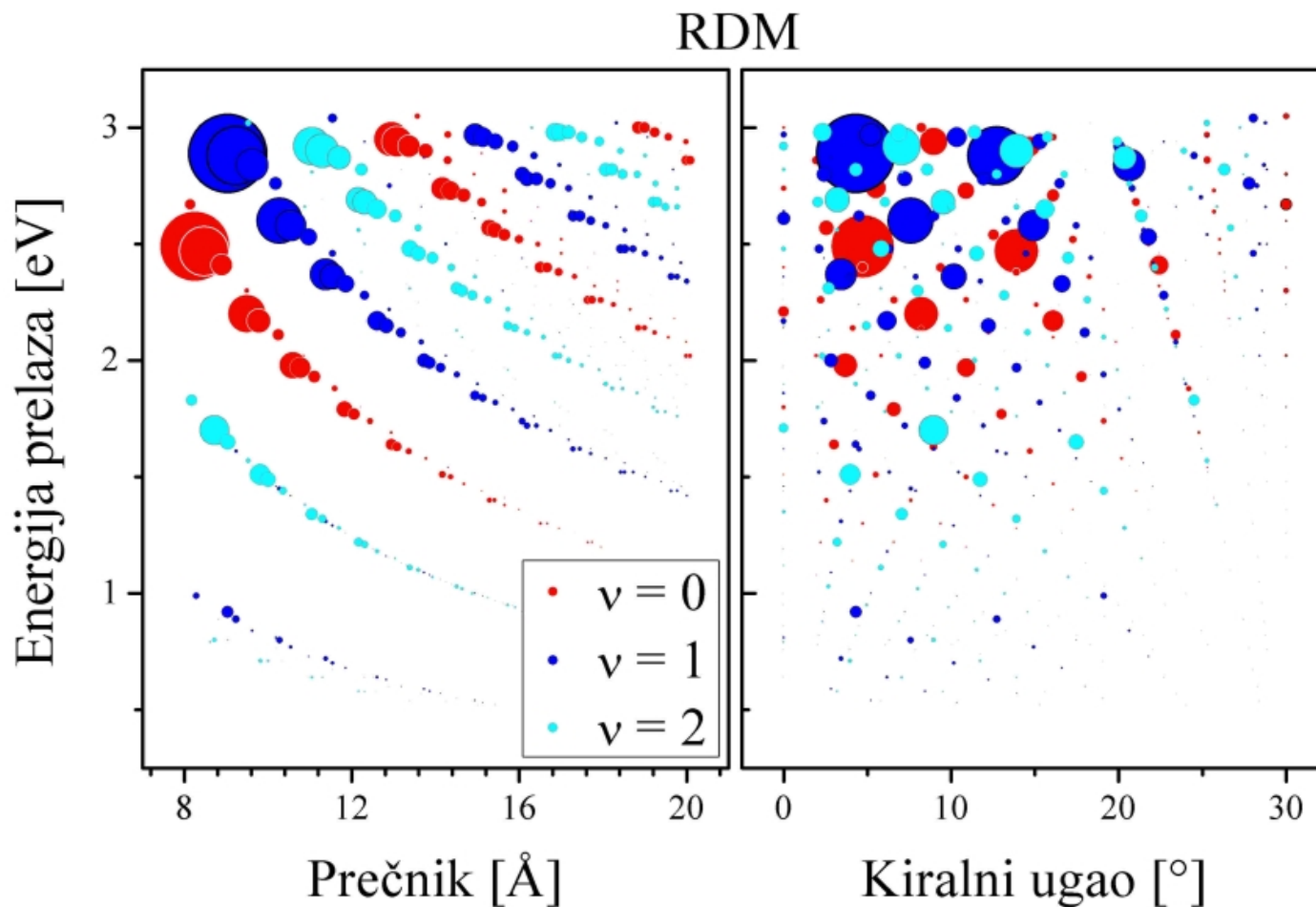
poluprovodne

# Optička svojstva

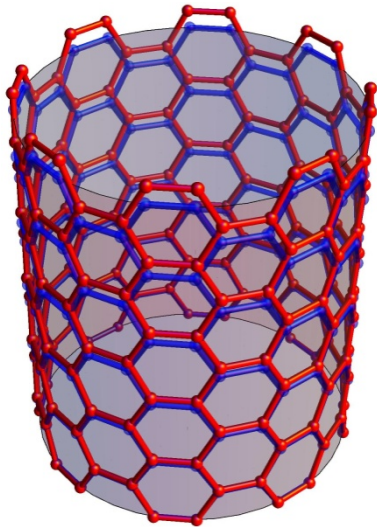




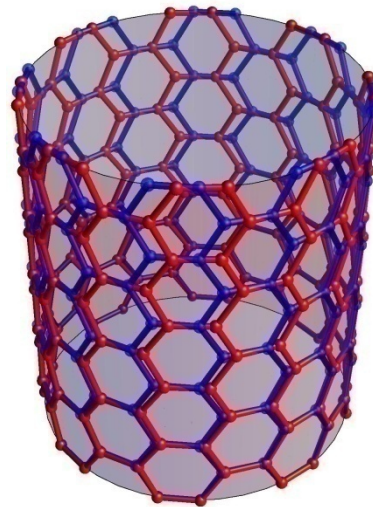
# Optička svojstva. Raman



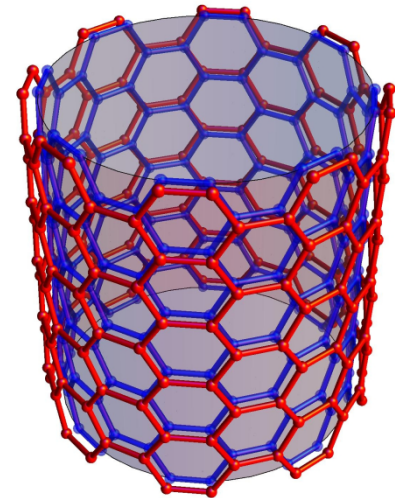
# Uticaj deformacija



istezanje

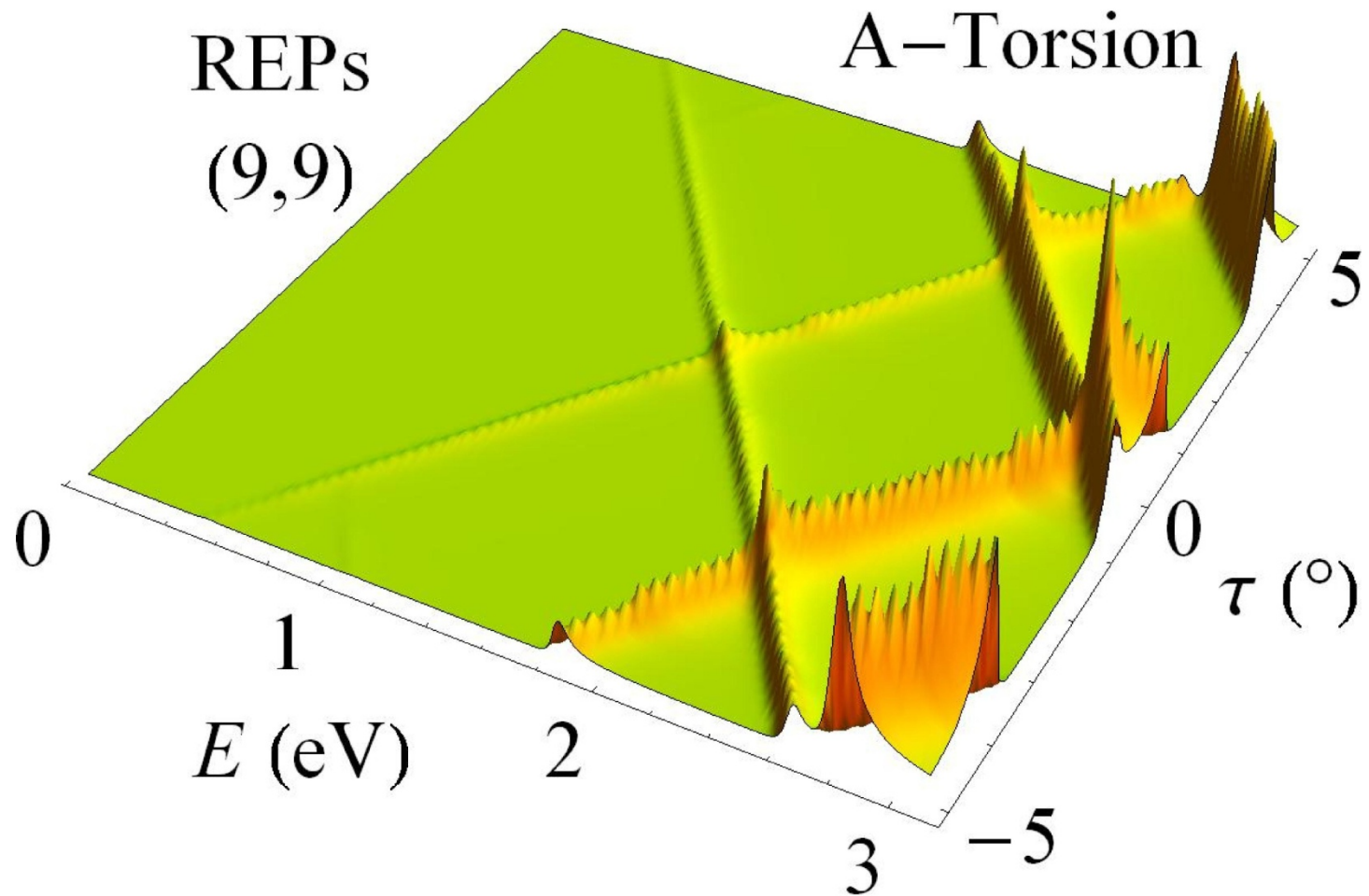


uvrtanje



disanje

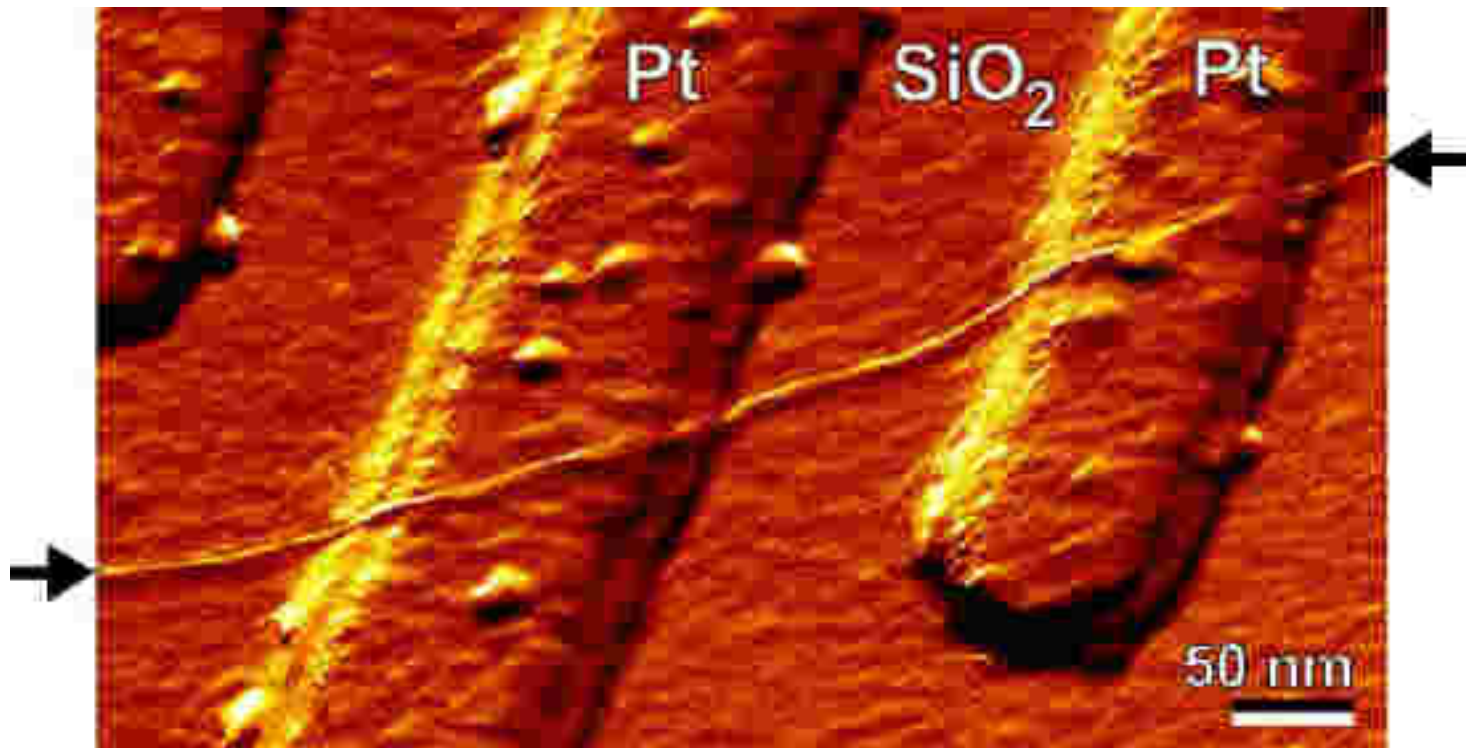
# Uticaj deformacija



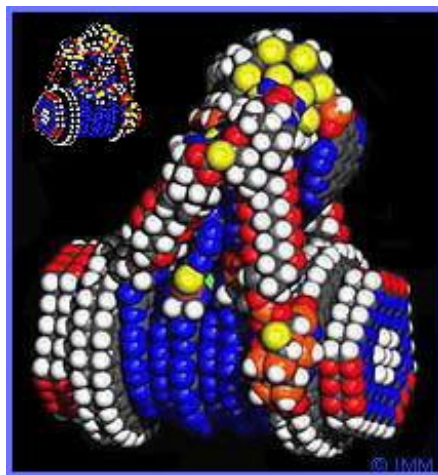
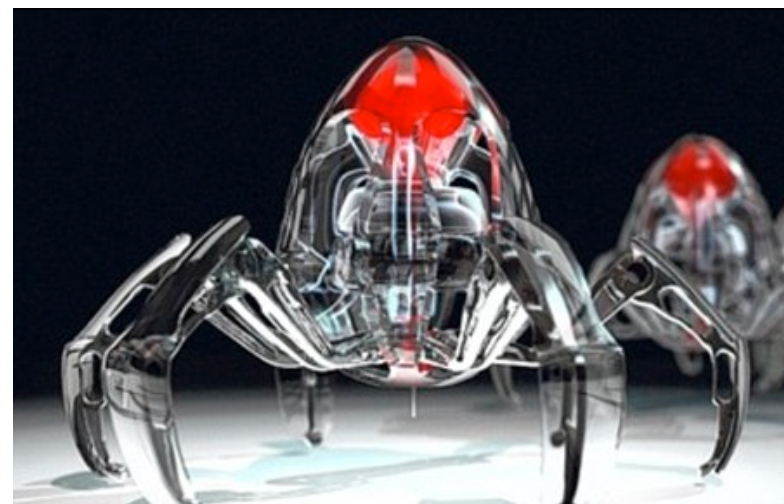
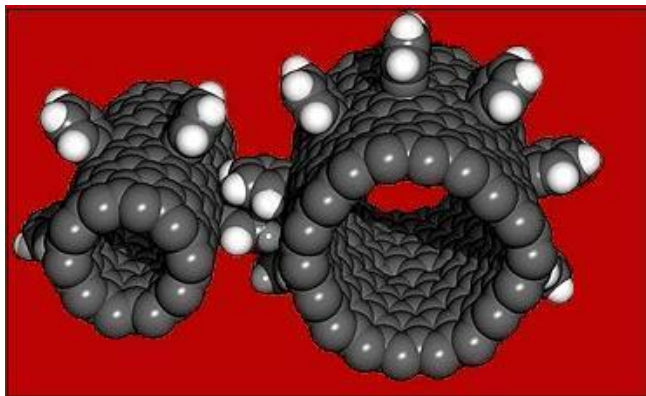
# Vrste nanotuba

Tip	Primeri
Halkogenidi	HfS <sub>2</sub> , MoS <sub>2</sub> , MoSe <sub>2</sub> , NbS <sub>2</sub> , TiS <sub>2</sub> , TiSe <sub>2</sub> , WS <sub>2</sub> , WSe <sub>2</sub> , ZrS <sub>2</sub>
Oksidi	BaTiO <sub>3</sub> , Ga <sub>2</sub> O <sub>3</sub> , PbTiO <sub>3</sub> , SiO <sub>2</sub> , TiO <sub>2</sub> , VO <sub>x</sub> , ZnO, ZrO <sub>2</sub>
Nitridi	BN, GaN
Halidi	NiCl <sub>2</sub>
Metalne tube	Bi, Co, Cu, Fe, Ni, Te, Au, Pt

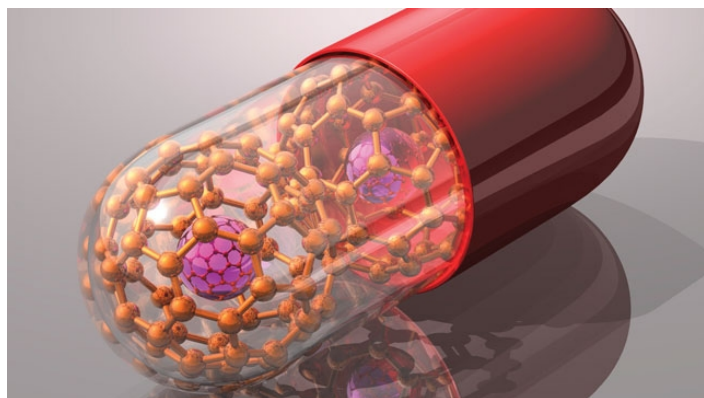
# Primena



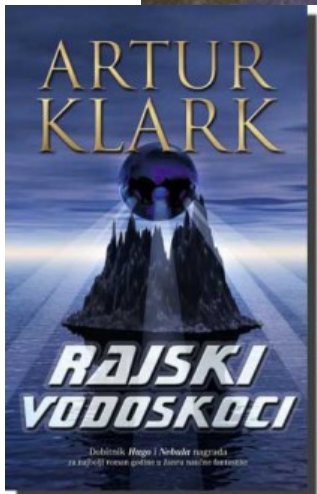
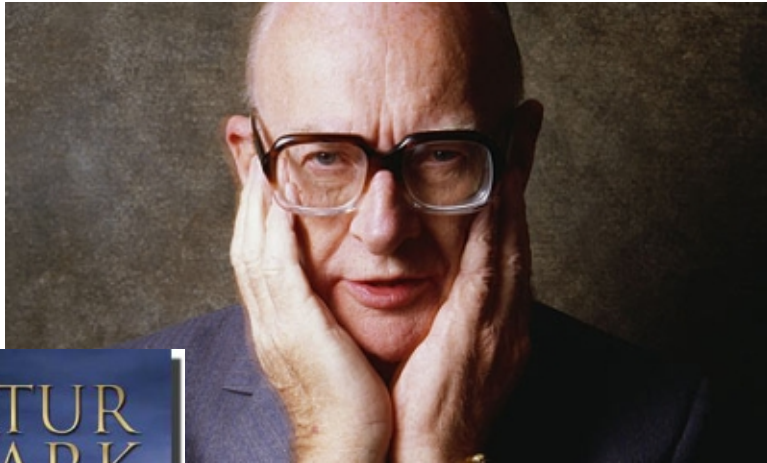
# Primena: nanomašine



# Primena: nanomašine



# Primena: lift

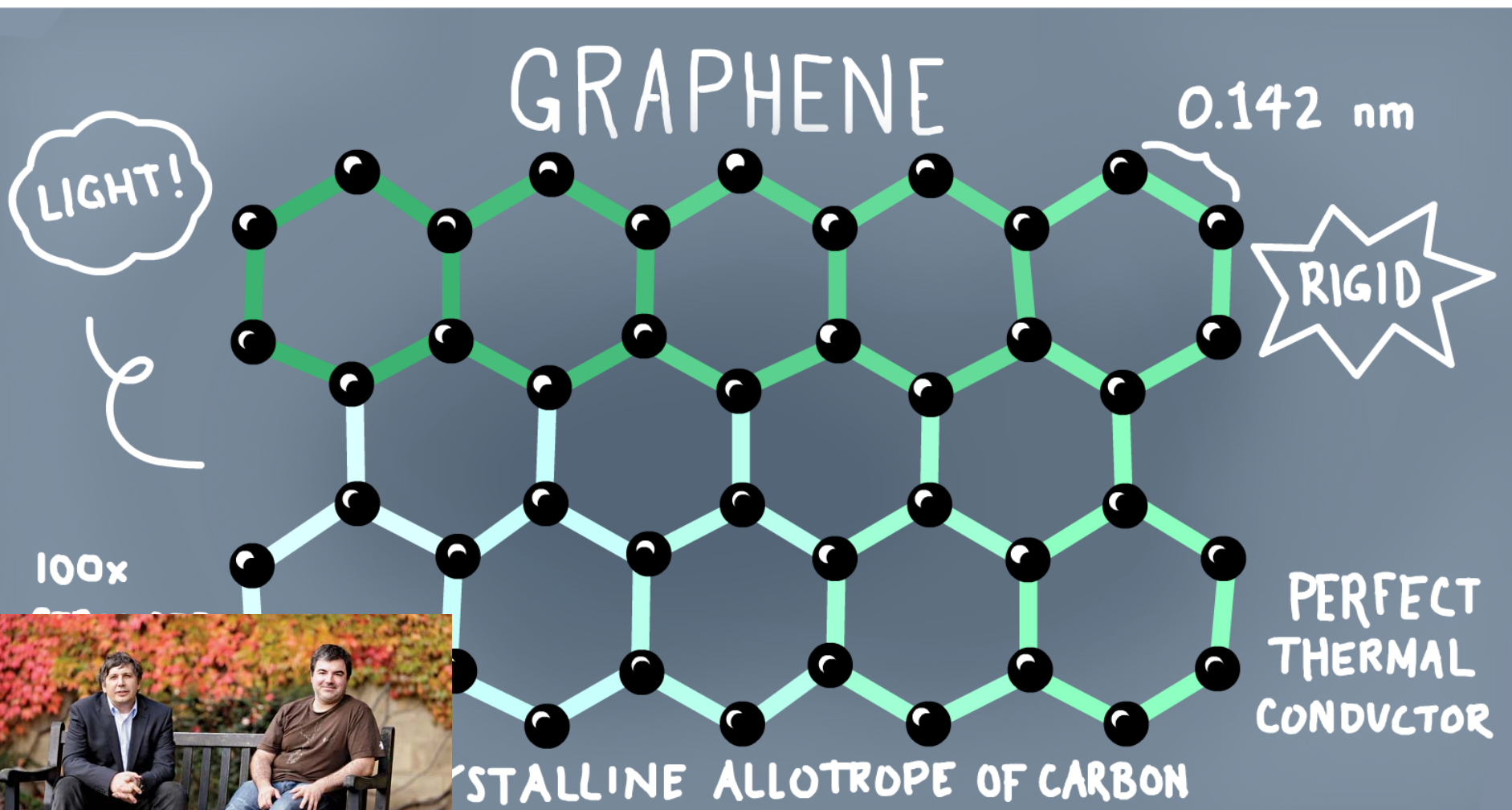


1979.





# Grafen



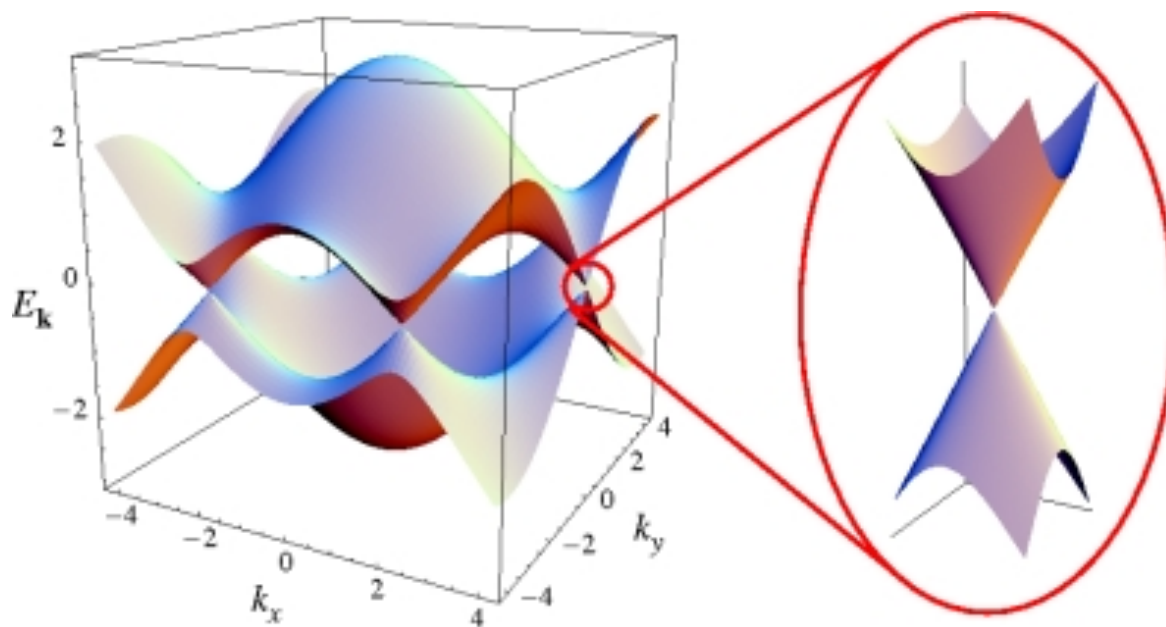
A. Geim i K. Novoselov NN 2010.



# Grafen

- Svojstva grafena
  - Dobra provodljivost
  - 200 puta čvršći od čelika
  - Tanak i lagan
  - Dobar provodnik toplote
  - Praktično providan
- Potencijalna primena
  - Ekрани osetljivi na dodir
  - Filteri za prečišćavanje vode
  - Elektronski elementi
  - Hemijski i bio - senzori
  - Baterije

# Grafen: Dirakovi elektroni



# Uместo zaključka

- Ogromna neistražena polja za buduća istraživanja.
- Veliki izazov za eksperiment (kreiranje novih eksperimenata, usavršavanje dosadašnjih, razvoj opreme...).
- Brojni zadaci za teoriju (preispitivanje dosadašnjih teorija i modela, stvaranje novih, mogućnost stvaranja realnih sistema na kojima bi se testirala teorija...)
- Velike mogućnosti i interes za primenu (što znači pouzdano finansiranje projekata...)

**Hvala na pažnji!**

