Nanostrukture i nanoelektronske naprave

(za čipove budućnosti)

Milan Ž. Tadić

Elektrotehnički fakultet, Univerzitet u Beogradu

Saradnja:

Vladimir Arsoski, Nemanja Čukarić,

Marko Grujić, Dejan Raković, *ETF*

F. M. Peeters, *University of Antwerp, Belgium*

Branimir Radisavljević, *EPFL, Switzerland*

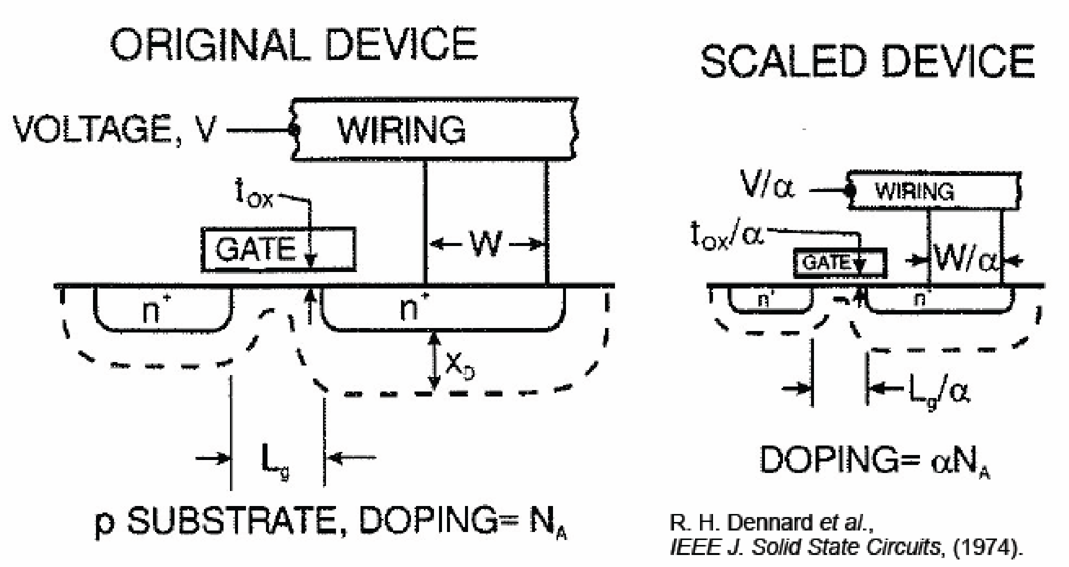
Mooreov zakon

~~Mičio Kaku, "Fizika budućnosti", Laguna, 2011, strana 32: "Murov zakon jednostavno kaže da se snaga kompjutera udvostručuje otprilike na svakih osamnaest meseci."~~

"The number of transistors that can be inexpensively placed on an integrated circuit is increasing exponentially, doubling approximately every two years."

- Najčešće citiranje: dve godine->18 meseci
- 2059. godine, na 100. rođendan integrisanog kola (CE skaliranje):
  - kritična dimenzija 0,25 nm
  - debljina oksida gejta 0,004 nm!? (EOT)
  - radni napon 2 mV
  - 64 eksabitni DRAM-ovi (eksa=milijardu milijardi)
- Mooreov zakon se odnosi na nivo integracije i ekonomičnost izrade integrisanog kola i nije vezan ni za jednu posebnu tehnologiju.

Skaliranje MOSFET-a



- Smanjenje dimenzija->efekti kratkog kanala:

- smanjenje napona praga;

- uvećanje DIBL efekta;

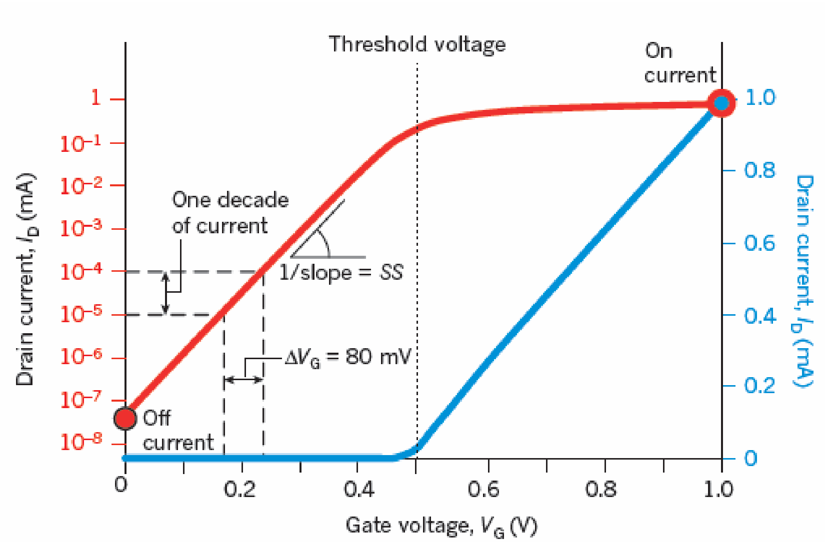
- povećanje potpražnog nagiba;

- efekat modulacije dužine kanala;

- efekti vrućih nosilaca;

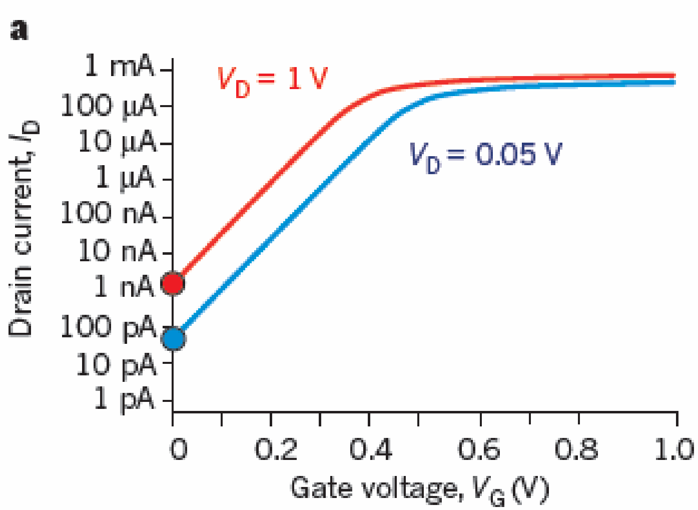
- ....

Prekidačke karakteristike

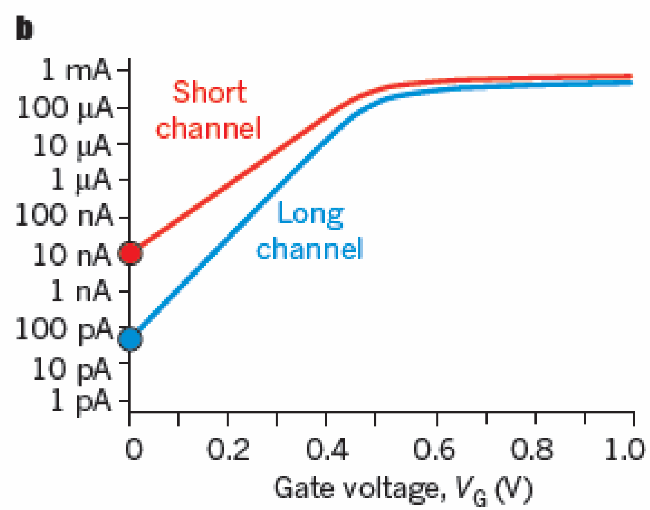


Dobar MOSFET:

- S<80 mV/dekada
- $I_{ON}/I_{OFF}>10^4$
- Zanemarljiv DIBL

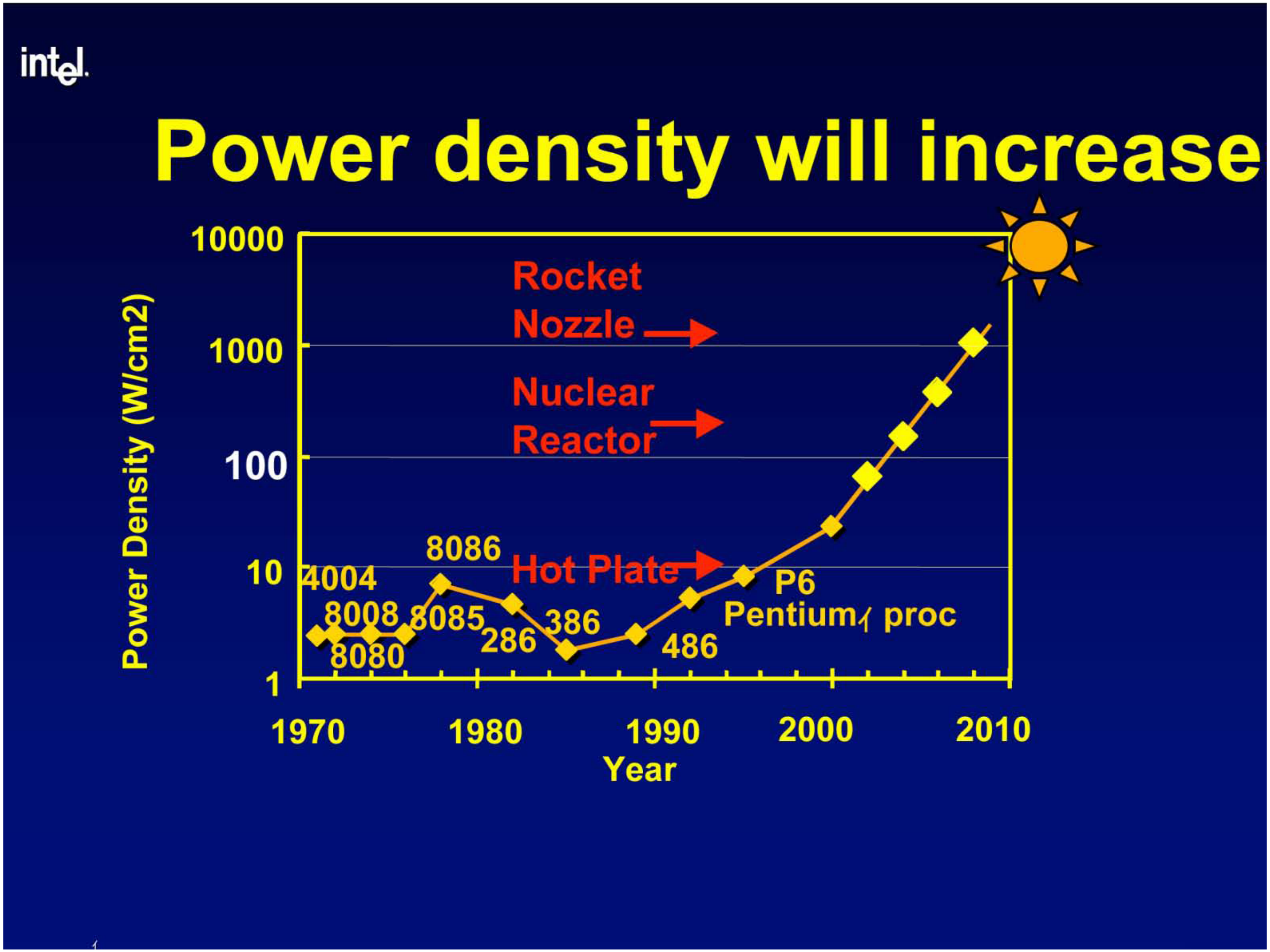


DIBL



Uvećanje potpražne struje

Gustina disipirane snage



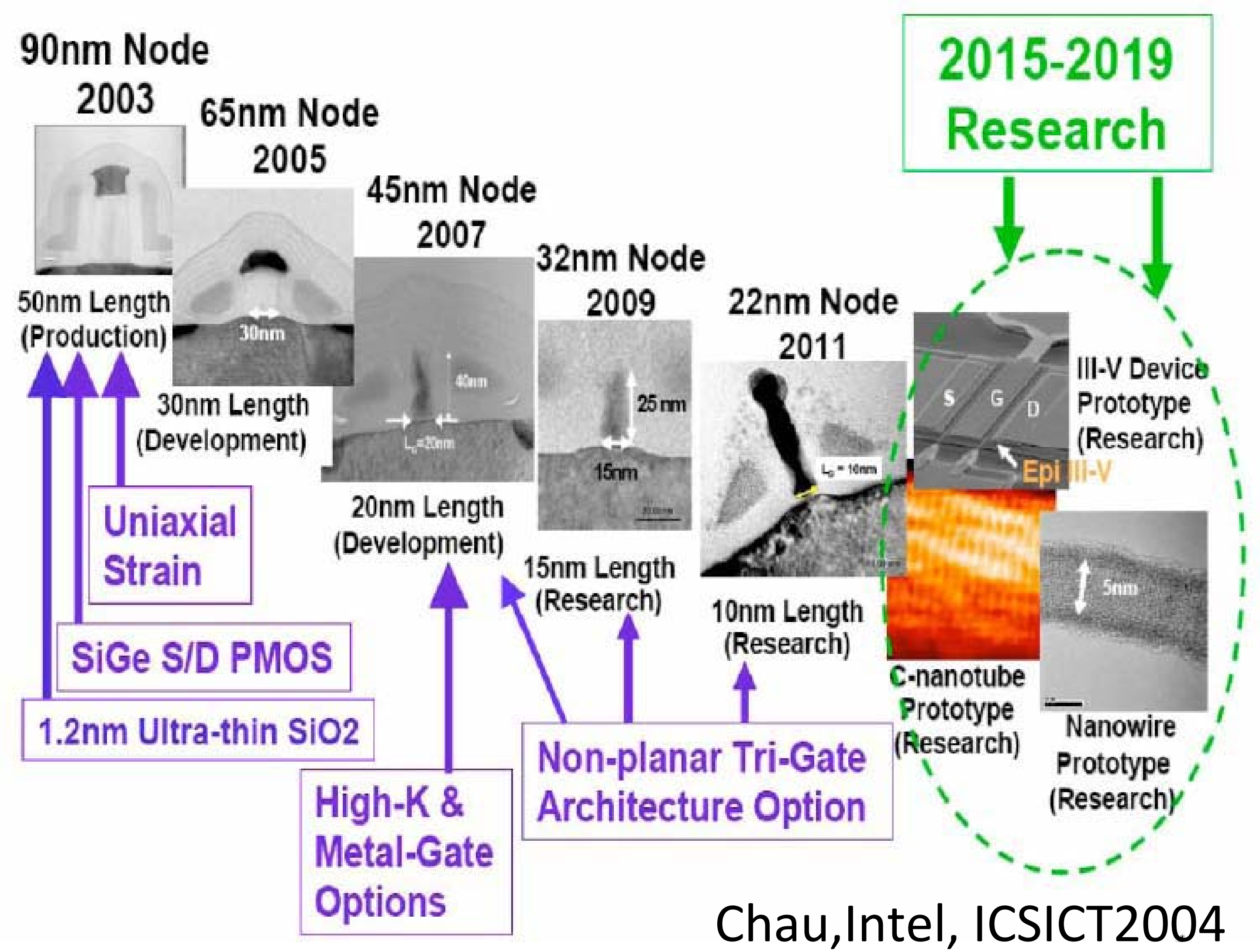
Hlađenje

Hladnjaci procesora: nekad i sad

danas

1993

Research roadmap for silicon

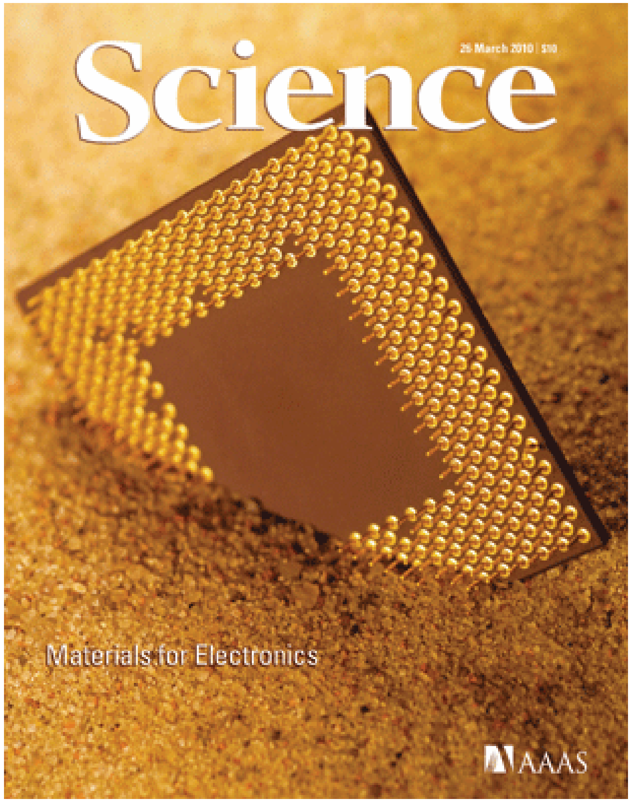


Chau,Intel, ICSICT2004

Moguća alternativna rešenja

- Multigejt MOSFET-ovi; TFET-ovi
- Multigejt MOSFET-ovi na bazi III-V jedinjenja (i CMOS!)
- MOSFET-ovi na bazi nanožica
- GFET-ovi
- CNTFET-ovi
- FET-ovi na bazi dihalkogenida
- Nove funkcionalnosti

“Zalazak” ere silicijuma?

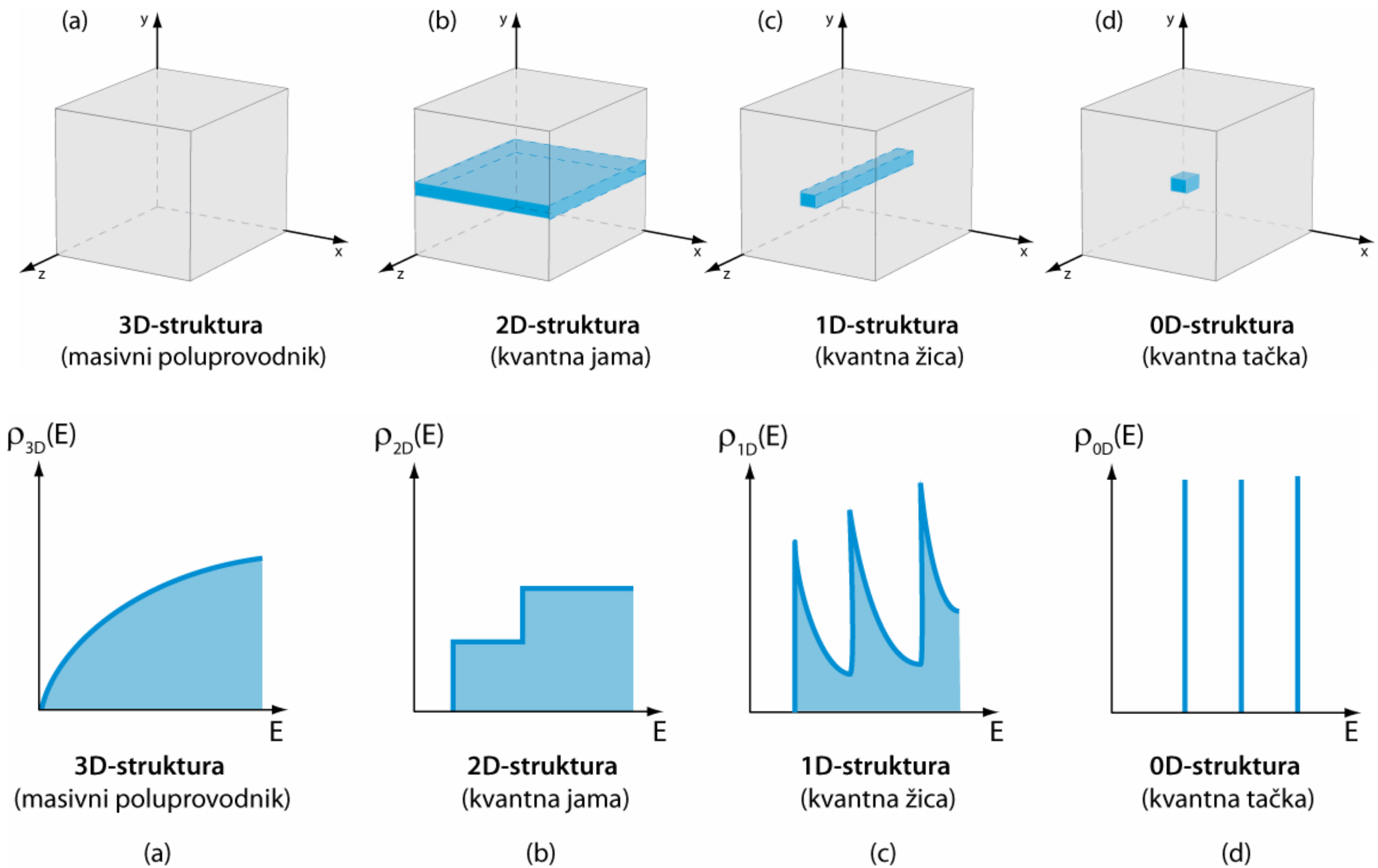


The push toward electronics that are smaller, faster, and more flexible requires either:

(1)new inorganic and organic materials,
(2)new functionality for silicon and
(3)new transistor designs.

Looking Beyond Silicon, Science, 327 (2010)
Silicon Electronics and Beyond, Nature, 479 (2011)

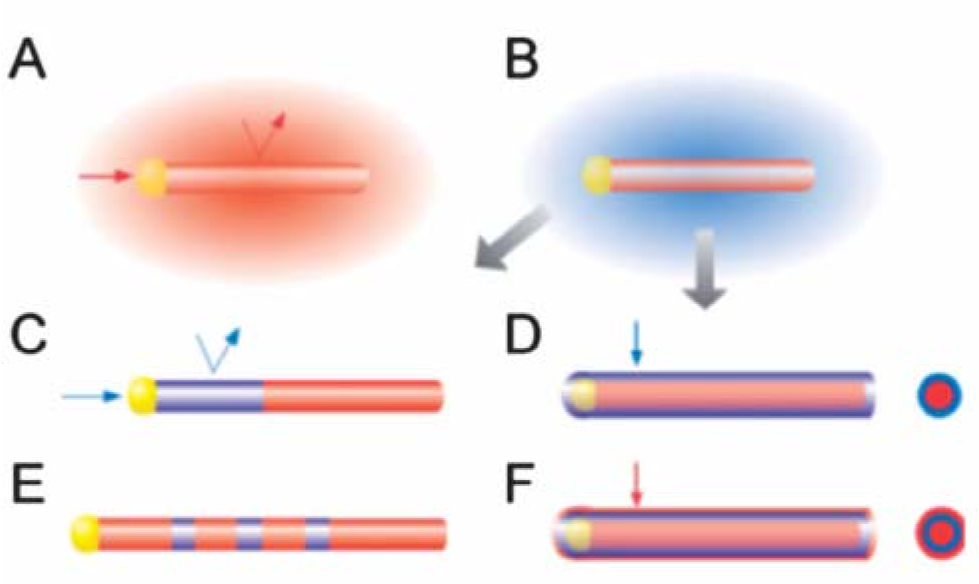
Poluprovodničke nanostrukture



Željko Pržulj, Uvod u nanonauke i nanotehnologije, 2013 (u štampi).

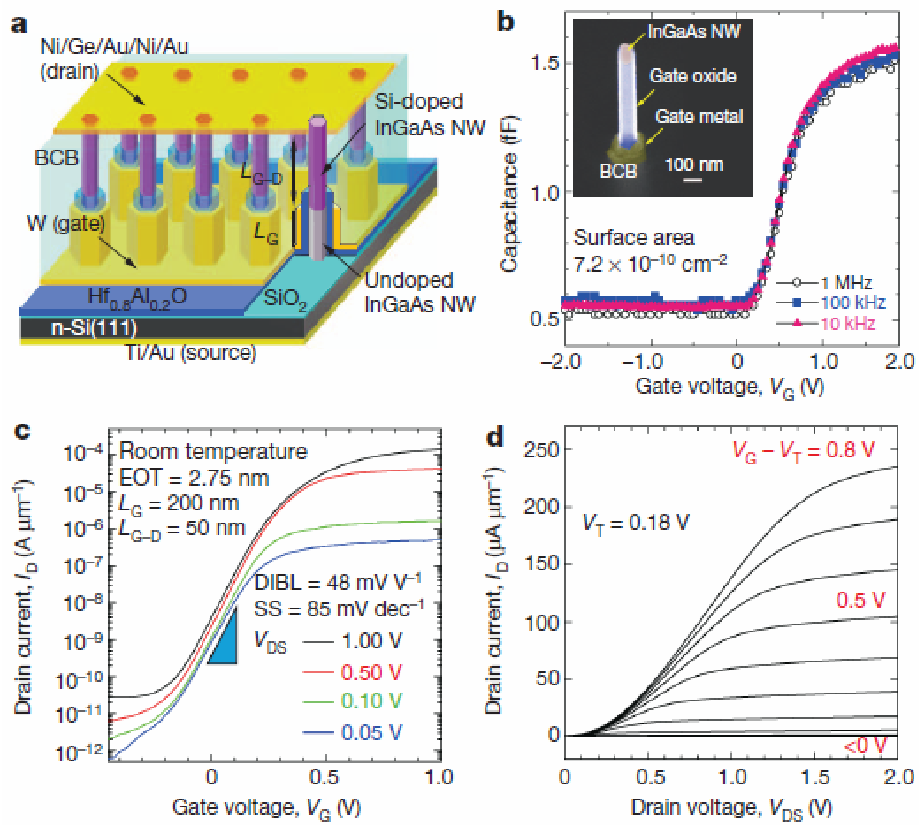
Poluprovodničke nanožice

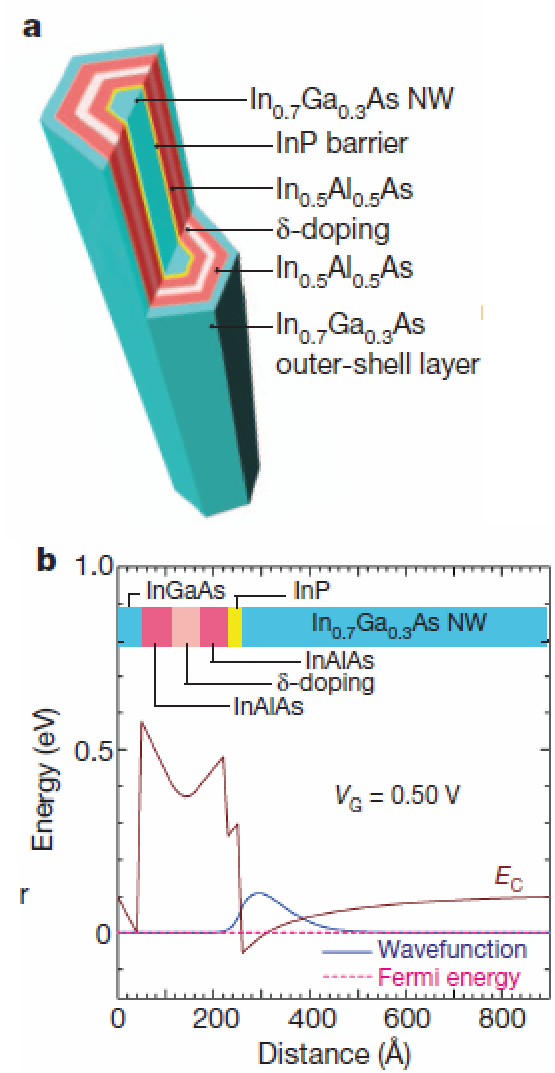
- Tehnike odozdo-nagore (B-U)
  - VLS tehnika
  - selektivna MOCVD
- tehnike odozgo-nadole (T-D)
  - litografija+ecovanje



VLS tehnika

GAA FET-ovi na bazi nanožica

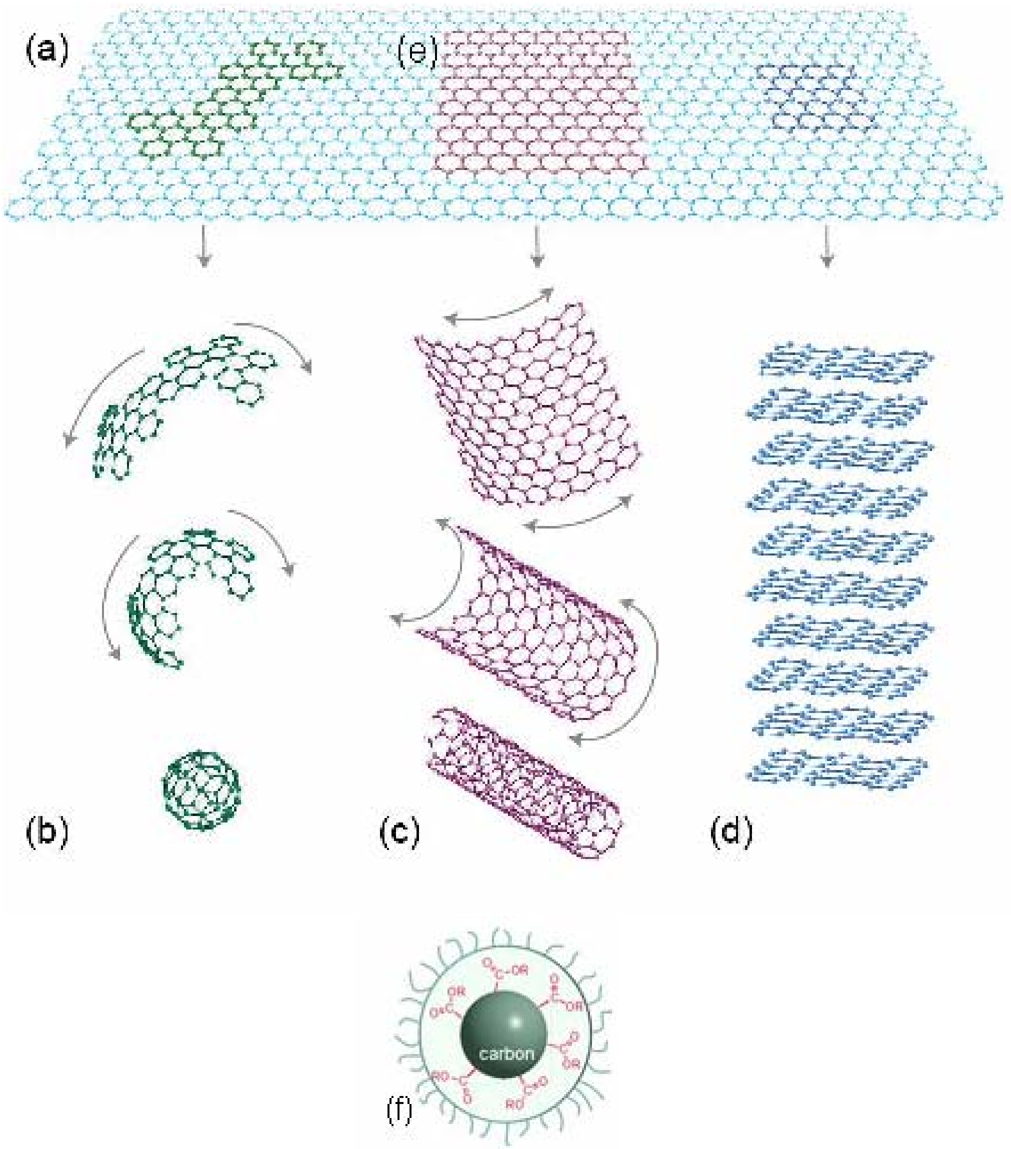




Za nanožicu sa više omotača:
S=75 meV/dekada; DIBL=35 mV/V;
$I_{ON}/I_{OFF}=10^8$.

Tomioka, Nature, 488, 189 (2012).

Grafen i ugljenične nanotube



Ugljenični nanomaterijali:
(a) Grafen
(b) Fuleren
(c) Nanotuba
(d) Grafit
(e) Grafenske nanotrake
(f) Ugljenične nanotačke (C-tačke)

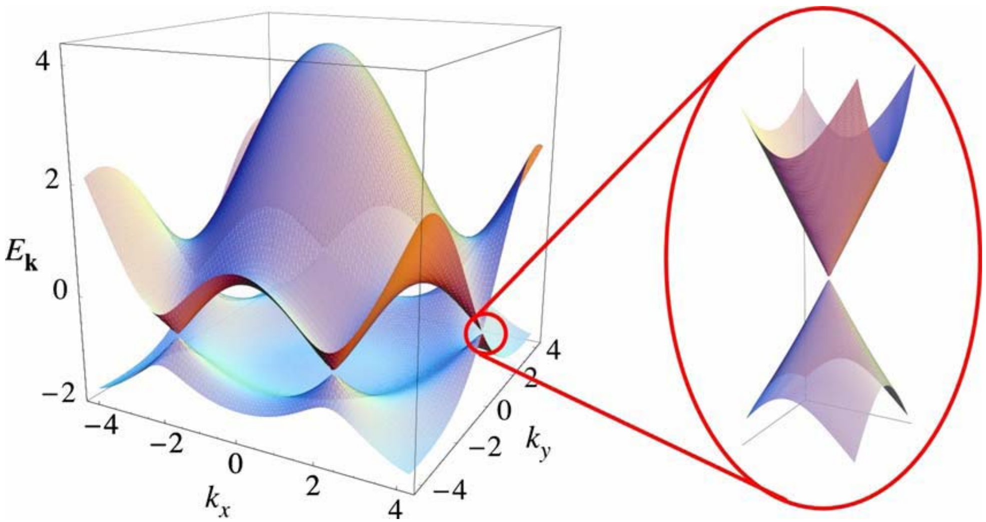
Grafen

Tehnika mehaničke eksfolijacije
("tehnika lepljive trake")

"Elektronika u olovci"
("Kvantna elektrodinamika u olovci")

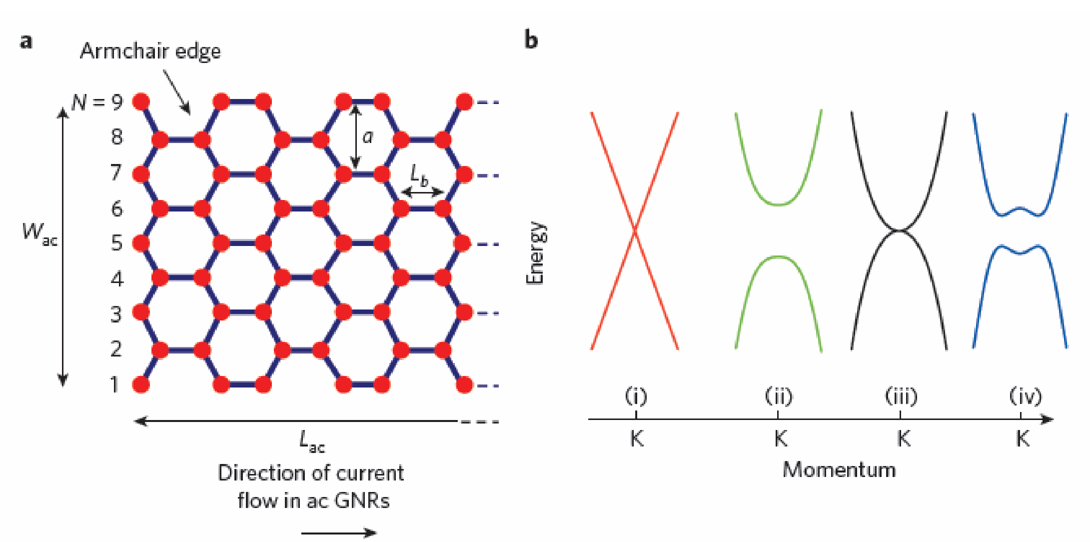
Novoselov, Geim, 2004

Elektroni u grafenu: Diracove čestice



Rezultati dobijeni pomoću metoda jake veze se odlično poklapaju sa eksperimentom.

E_g=0: poluprovodnik bez energijskog procepa. E_F=0; Diracov Hamiltonian: $H=v_F\sigma\mathbf{p}$

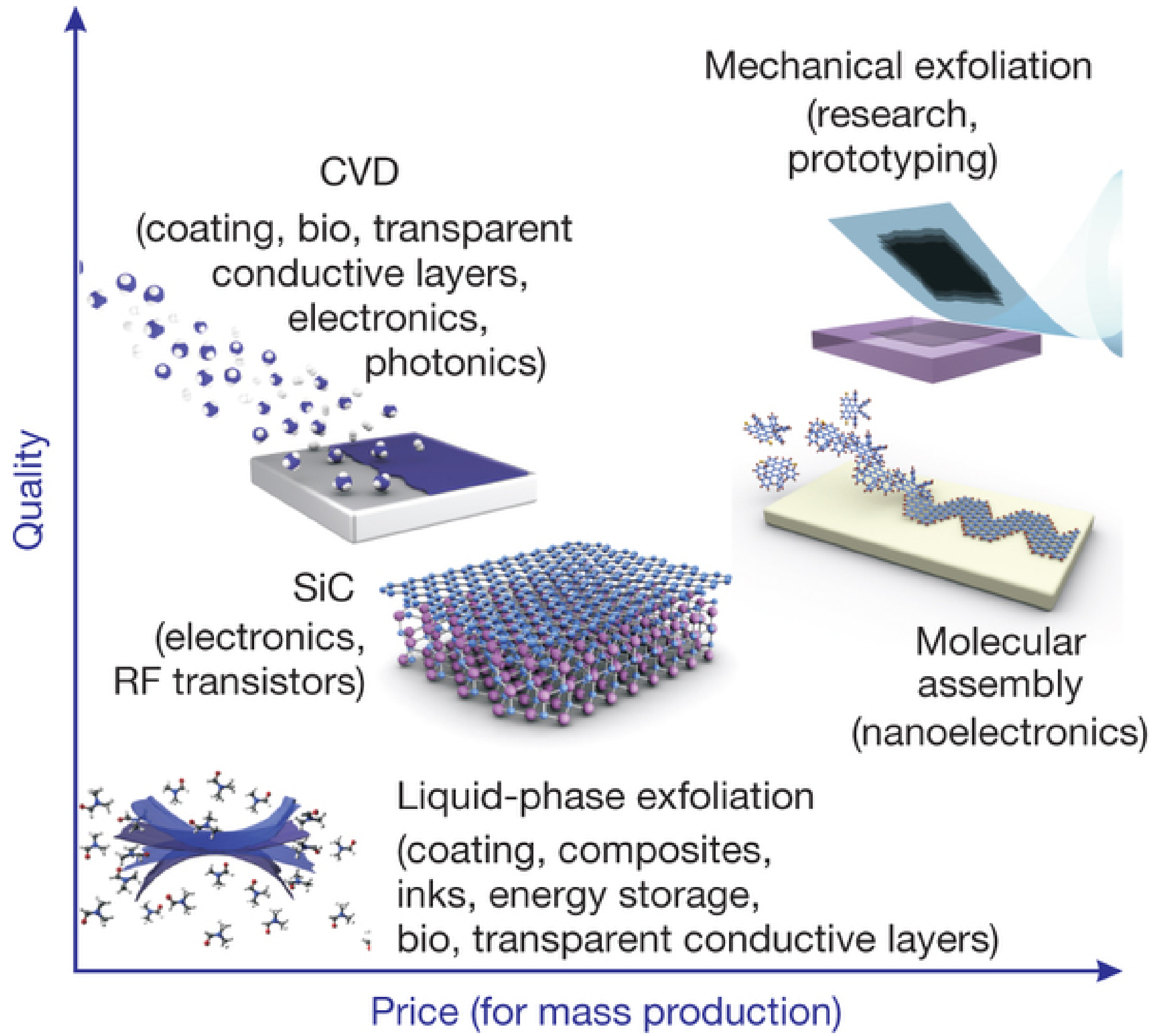


(i) jednoslojni grafen
(ii) jednoslojna nanotraka
(iii) dvoslojni grafen
(iv) dvoslojni+el. polje

Grafen: fabrikacija

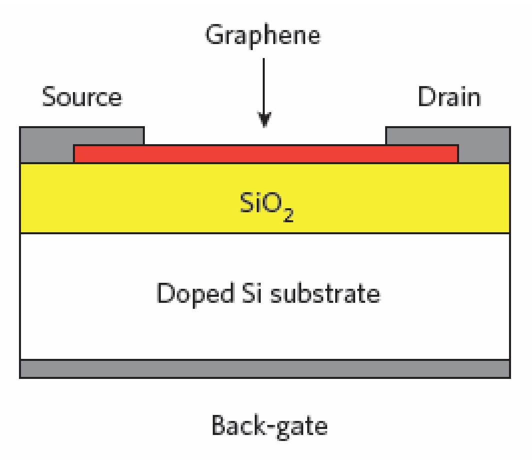
CVD: prenos na drugi supstrat;

SiC: epitaksijalni grafen

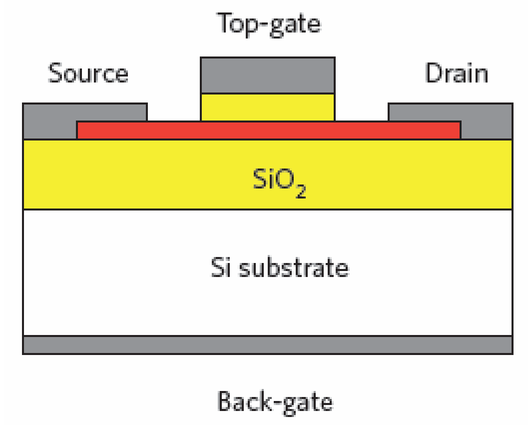


Novoselov , Nature, 490, 192 (2012)

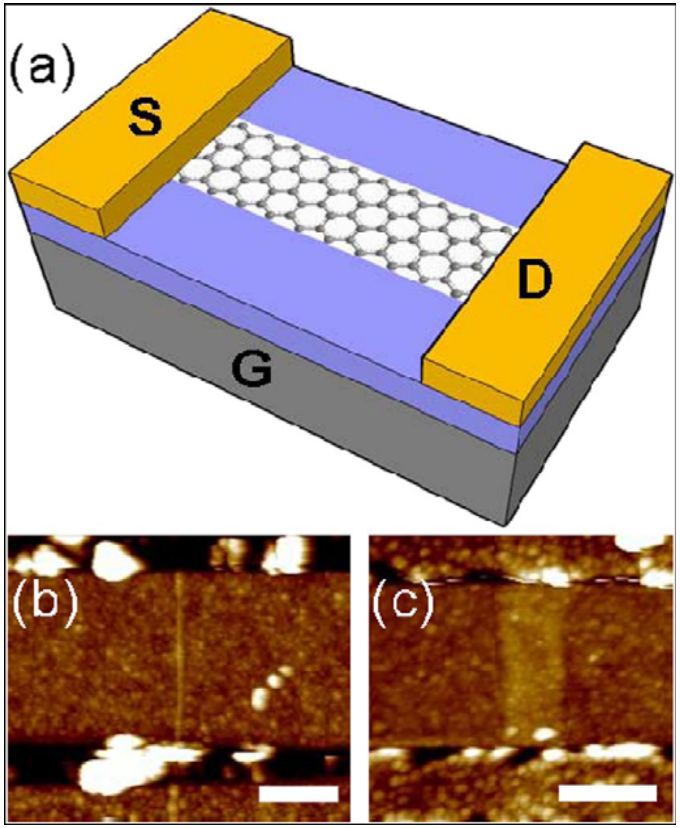
GFET



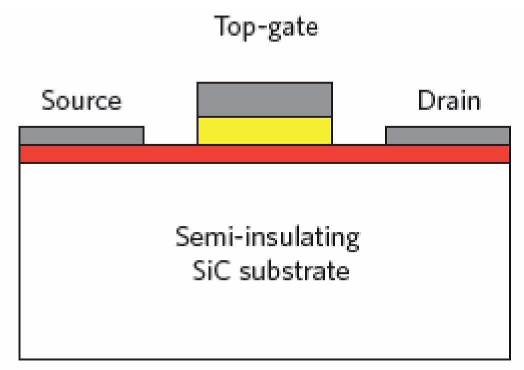
Eksfolirani grafen,
Novoselov, 2004



Preneseni grafen,
Lemme, 2007



FET na bazi grafenske nanotrake,
Wang, 2008.



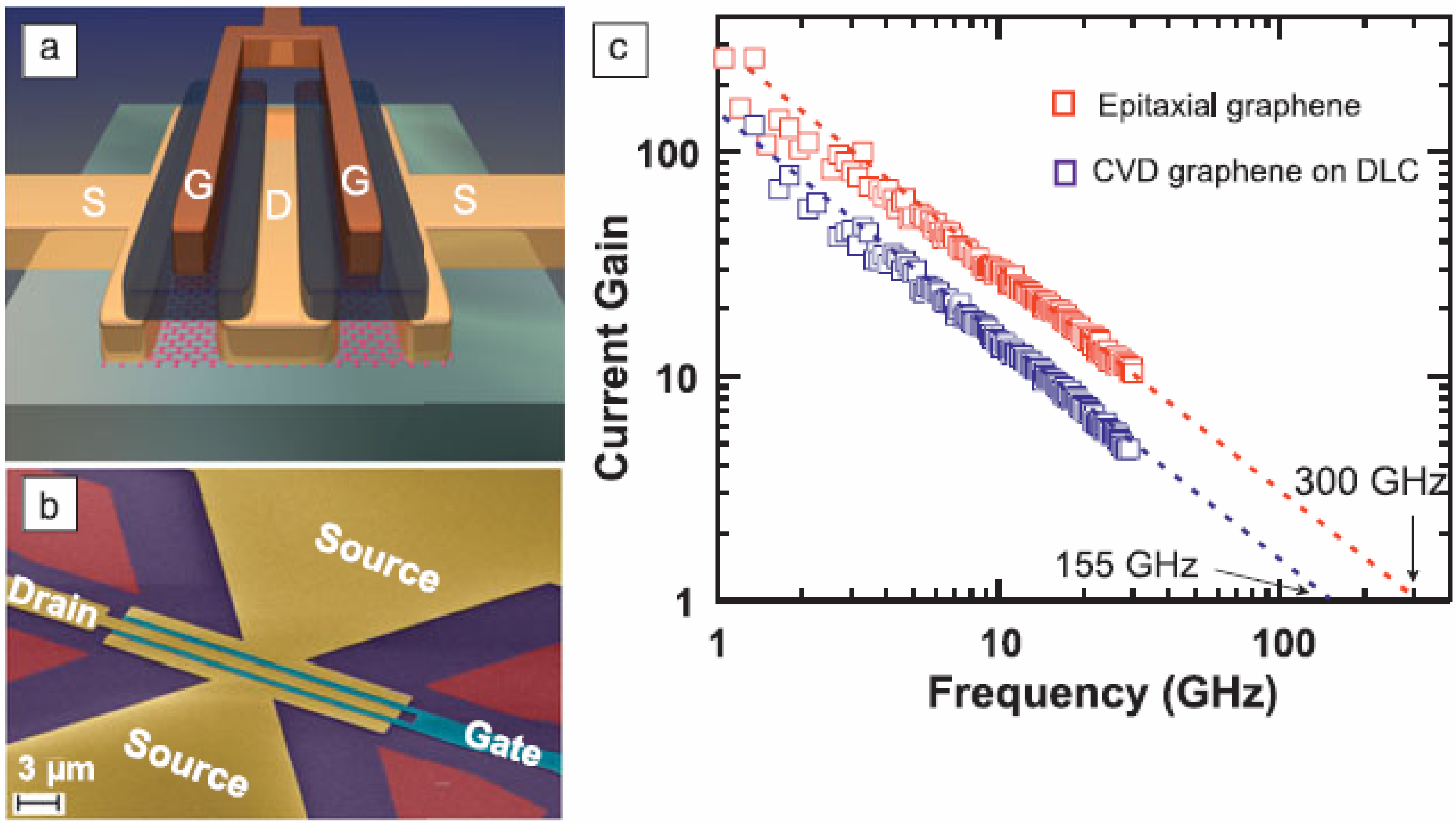
Epitaksijalni grafen,
Kedzierski, 2008

Schwierz, Nature Nanotechnology, 5, 487, 2010

Grafen: svojstva i primena u elektronici

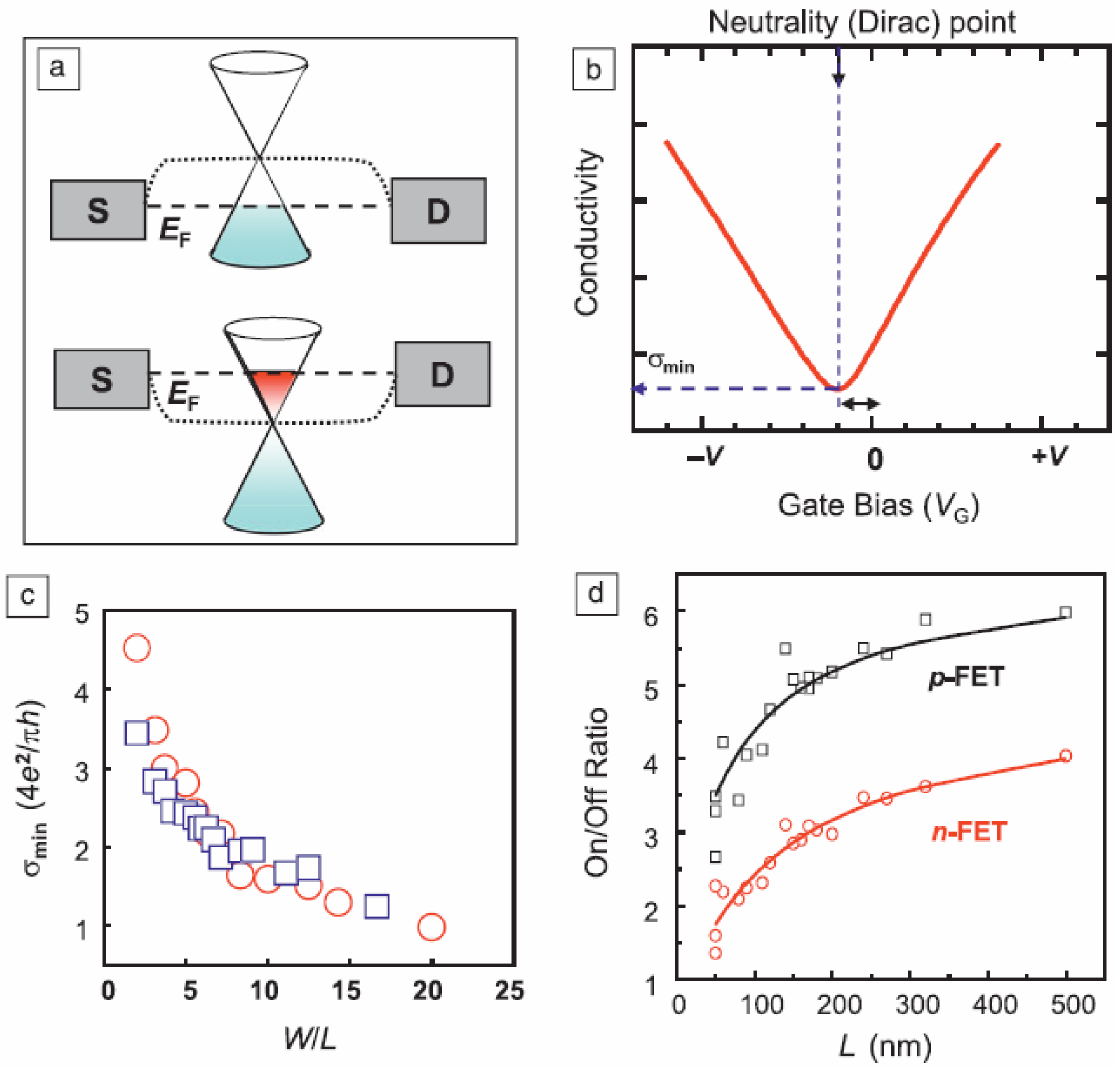
Metod	Veličina kristalita (μm)	Veličina uzorka (mm)	Pokretljivost (sobna temp.) (cm^2/Vs)	Primena
Mehanička eksfolijacija	>1000	>1	$>2x10^5$	Istraživanja
CVD	1000	~1000	10^4	Elektronika, fotonika, senzori
SiC	50	100	10^4	Elektronika

GFET: frekventne karakteristike



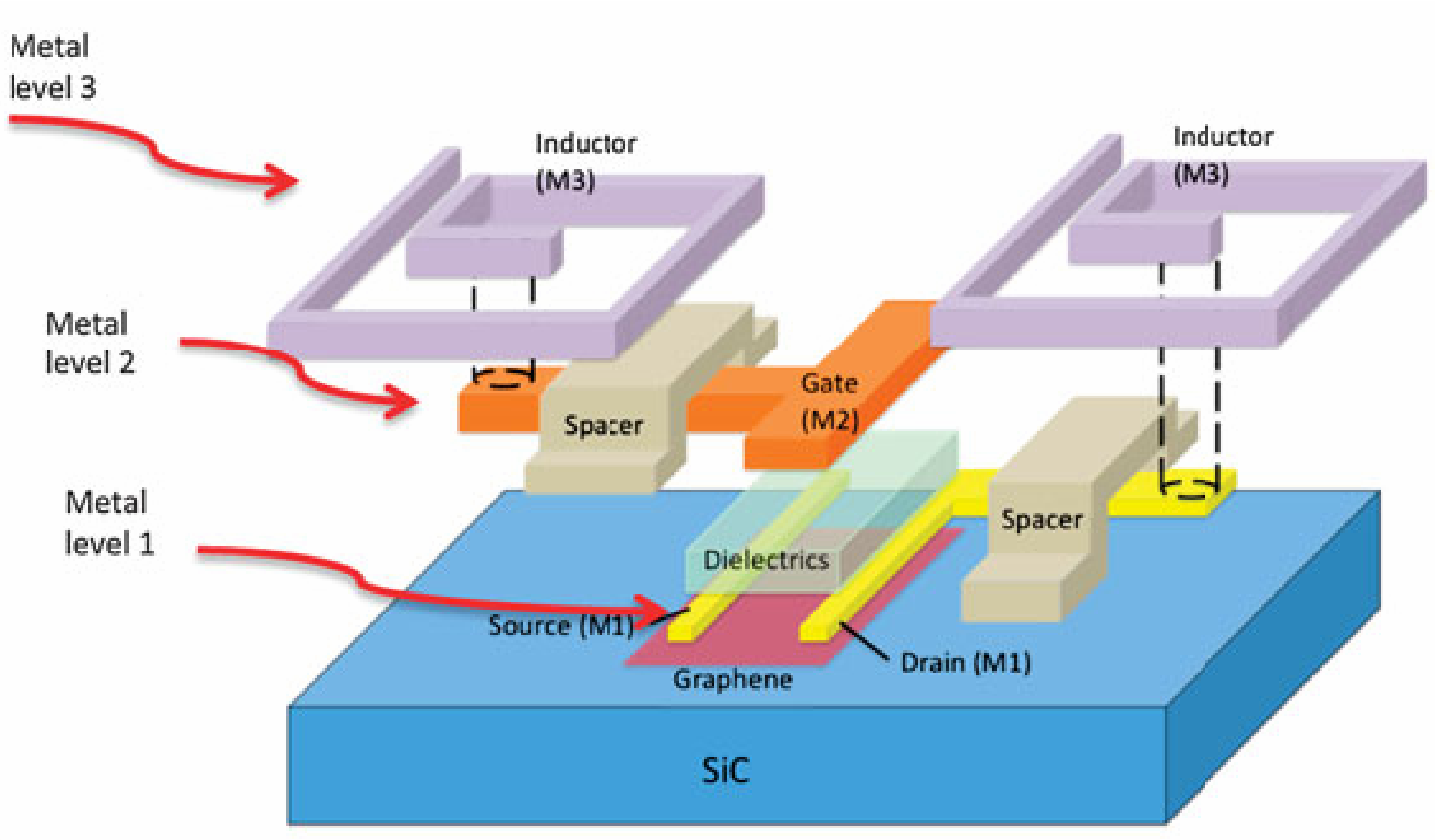
Avouris, MRS Bulletin, 37, (2012)

GFET: prekidačke karakteristike



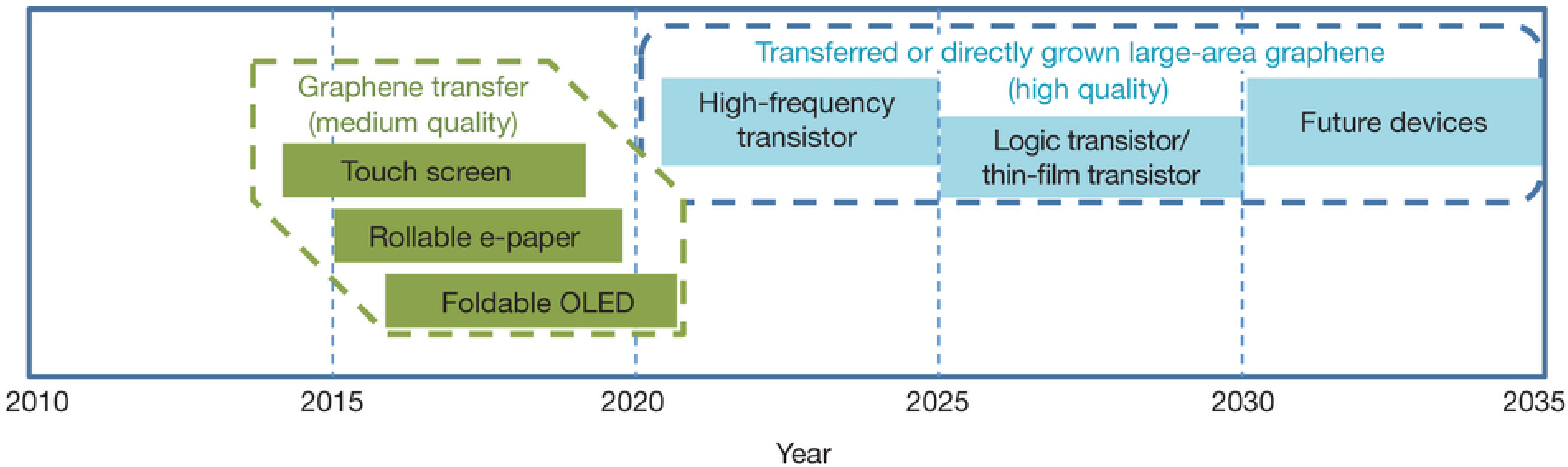
Avouris, MRS Bulletin, 37, (2012)

GFET integrisano kolo: tek 2011



Lin, Science, Science, 332, 1294 (2011)

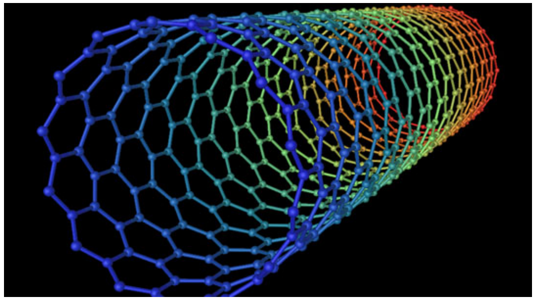
Technology roadmap for graphene



Novoselov , Nature, 490, 192 (2012)

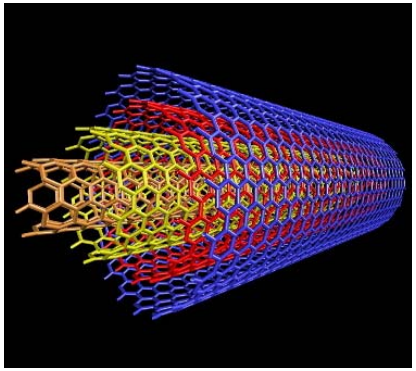
Struktura ugljeničnih nanotuba

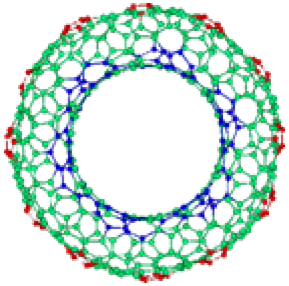
Jednoslojne nanotube (*single-walled*)



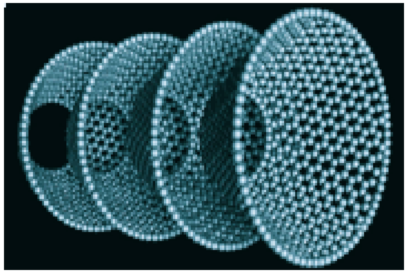
Višeslojne nanotube (*multi-walled*)

Iijima, 1991

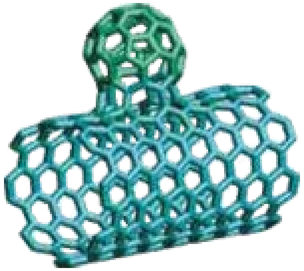




Nanotorus – u zavisnosti od prečnika mogu imati dobre magnetne momente, termičku stabilnost, itd.



Nanopupoljci (*nanobud*) – kovalentna veza nanotuba i fulerena; dobri emiteri polja, u kompozitnim materijalima poboljšavaju mehaničke osobine, itd.

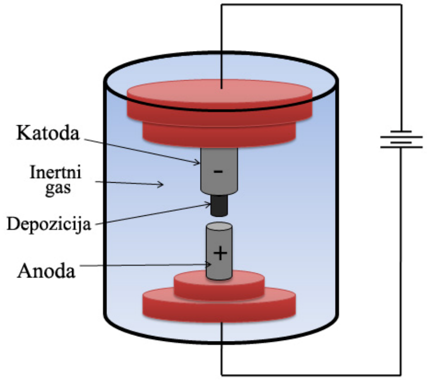


Nanotube naslagane u obliku kupe (*cup-stacked CNTs*) – dobre poluprovodničke osobine zbog složenih mikrostruktura.

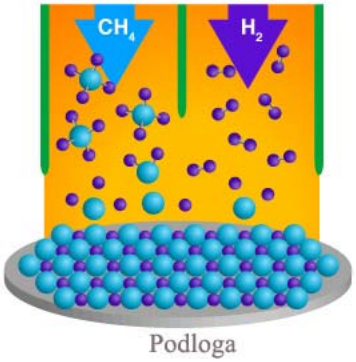
Sinteza ugljeničnih nanotuba

- Lučno pražnjenje
- Laserska ablacija
- Hemijska depozicija

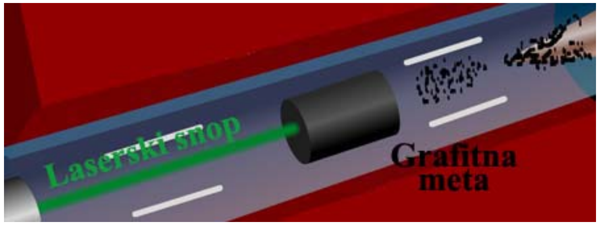
Lučno pražnjenje

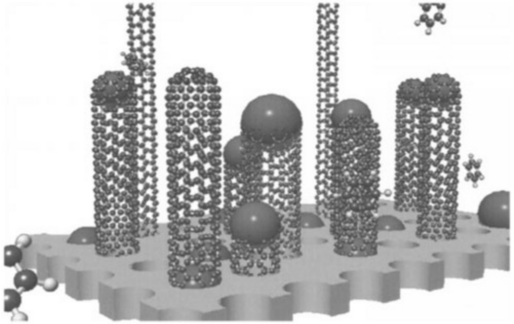


Hemijska depozicija iz parne faze (CVD)



Laserska ablacija

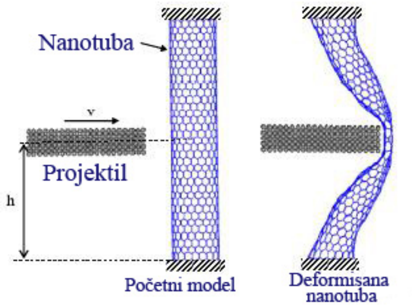




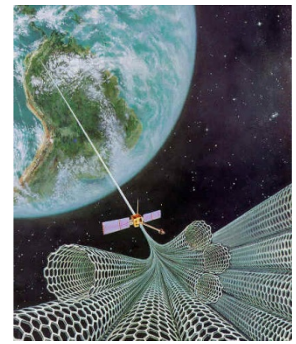
Primena ugljeničnih nanotuba

Mehaničke osobine

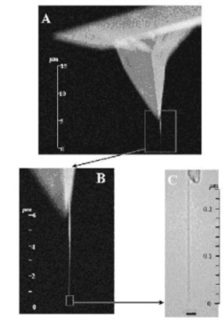
Zaštitna odeća



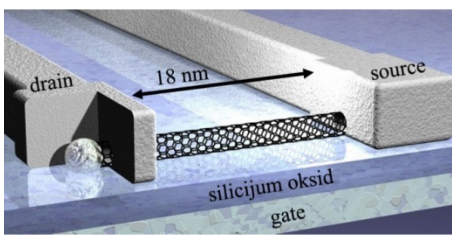
Svemirski lift



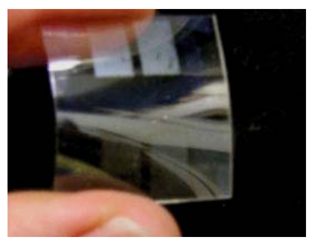
Vrh AFM-a



Tranzistori



Fleksibilne baterije

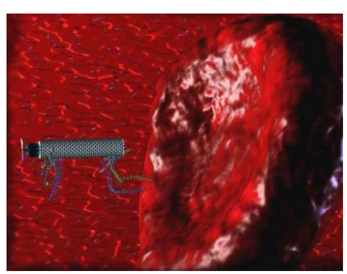


CNT TV

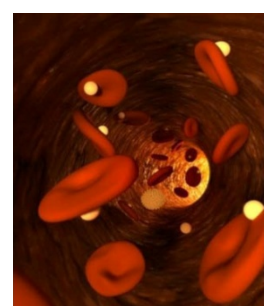
Primene u elektrotehnici

Primena u medicini

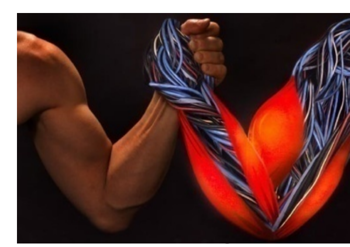
Biokompatibilne elektrode



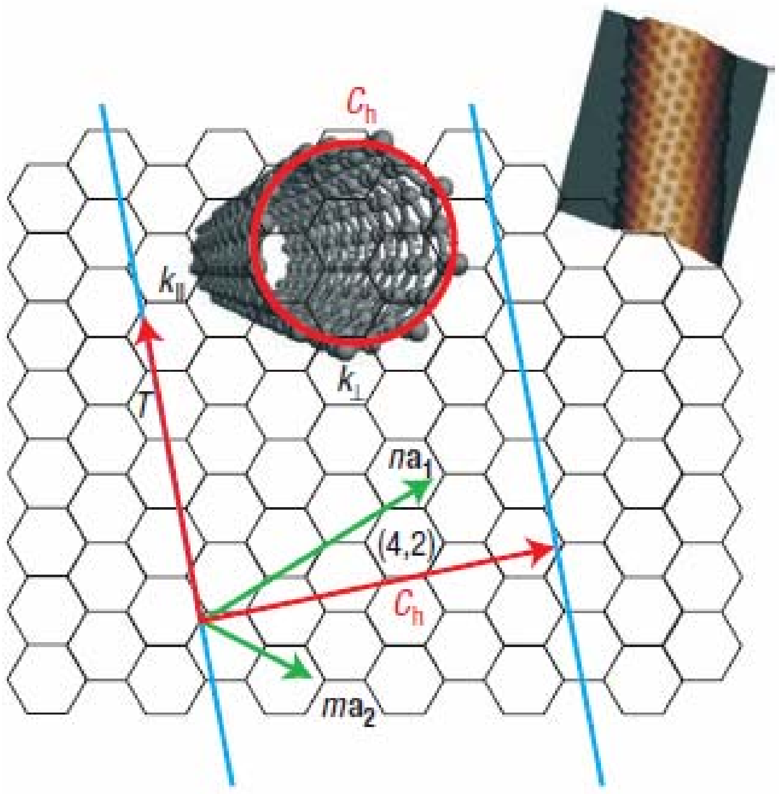
Transport lekova

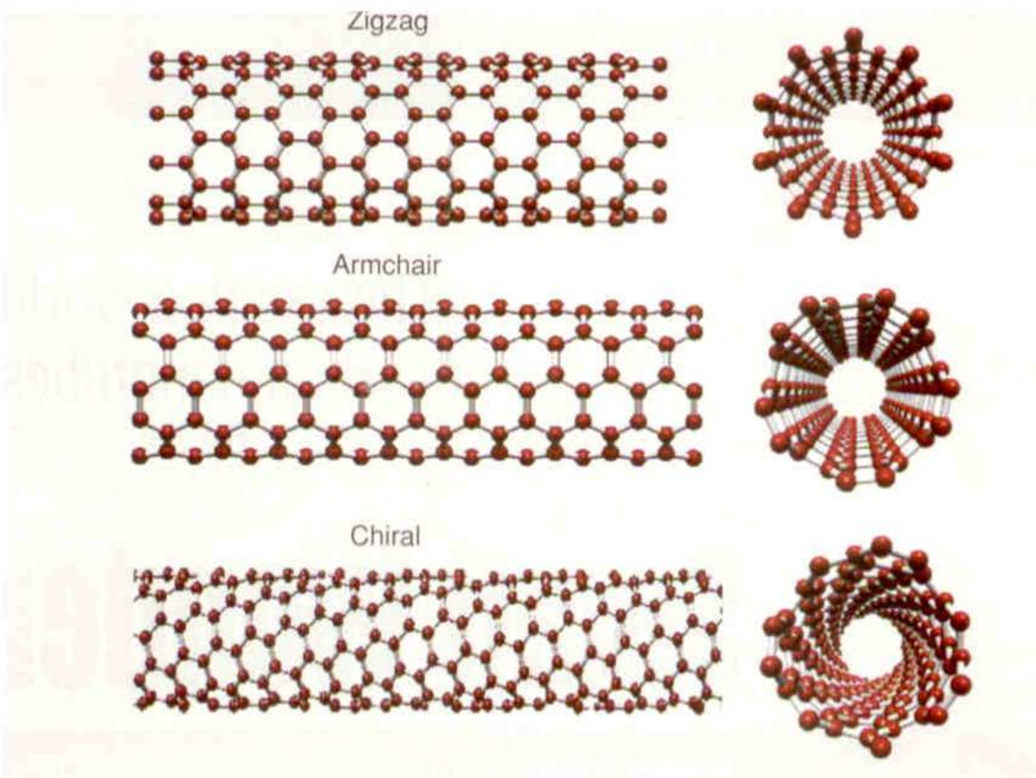


Veštački mišići



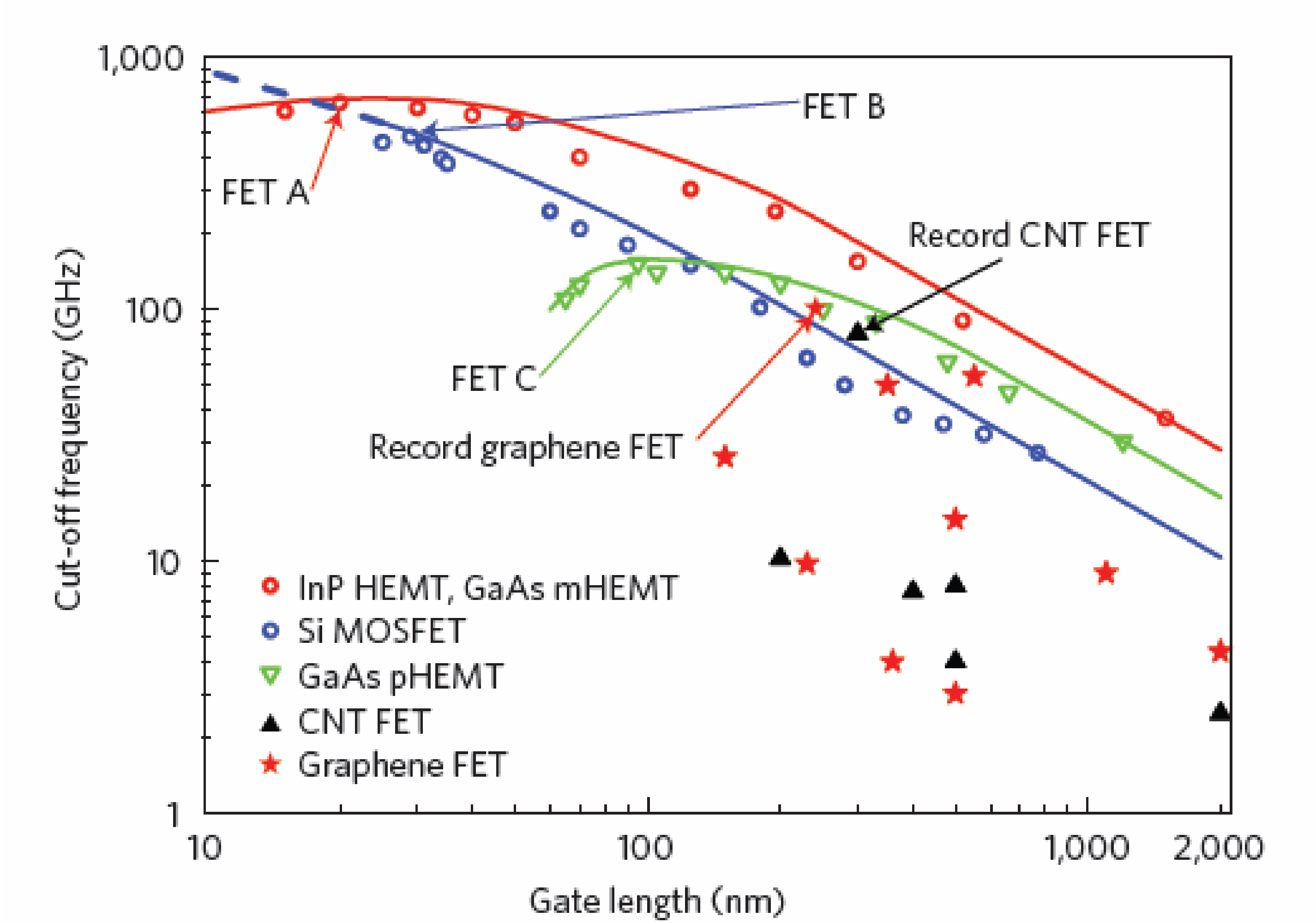
CNT: metalne ili poluprovodne





Cik-cak: poluprovodnik ili metal u zavisnosti od prečnika
Fotelja: uvek metal
Hiralna: po pravilu poluprovodnici

Presečne učestanosti raznih tranzistora (stanje 2010)

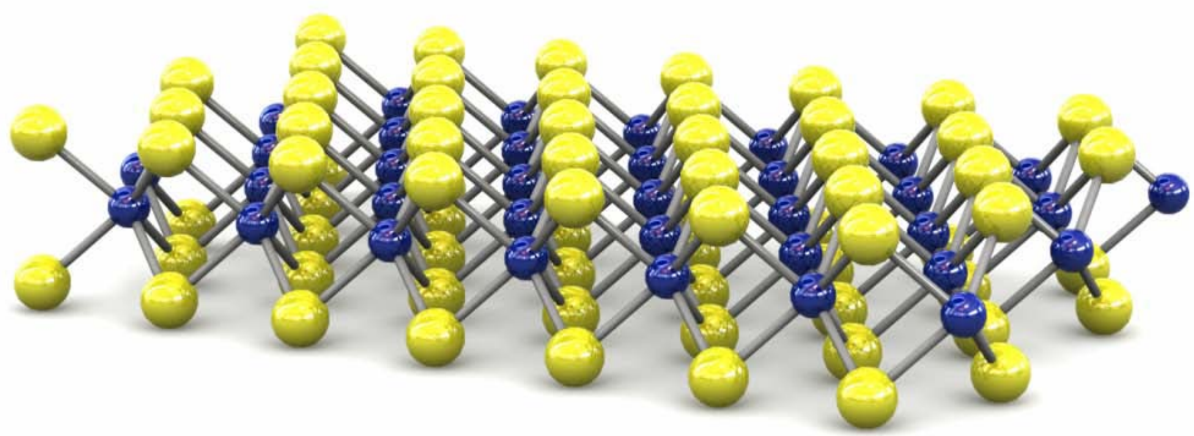


Schwierz, Nature Nanotechnology, 5, 487 (2010)

Grafen nije sam

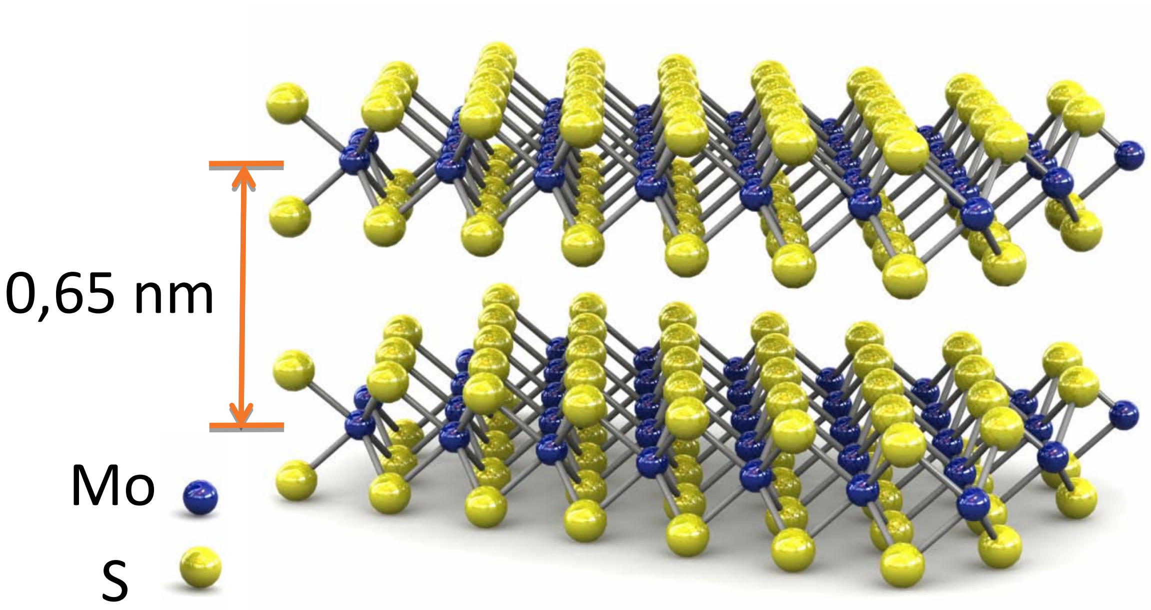
Provodne osobine	Materijal	Moguća primena
Metalne, CDW, superprovodne	$NbSe_2$, NbS_2, $NbTe_2$, TaS_2, $TaSe_2$, $TaTe_2$,	međuveze, Josephsonovi spojevi, SC kubiti
polumetalne	$TiSe_2$, grafen	međuveze
poluprovodne	MoS_2, $MoSe_2$, WS_2, WSe_2	tranzistori, senzori
izolacione	BN	razdvojni slojevi (baferi)

MoS_2



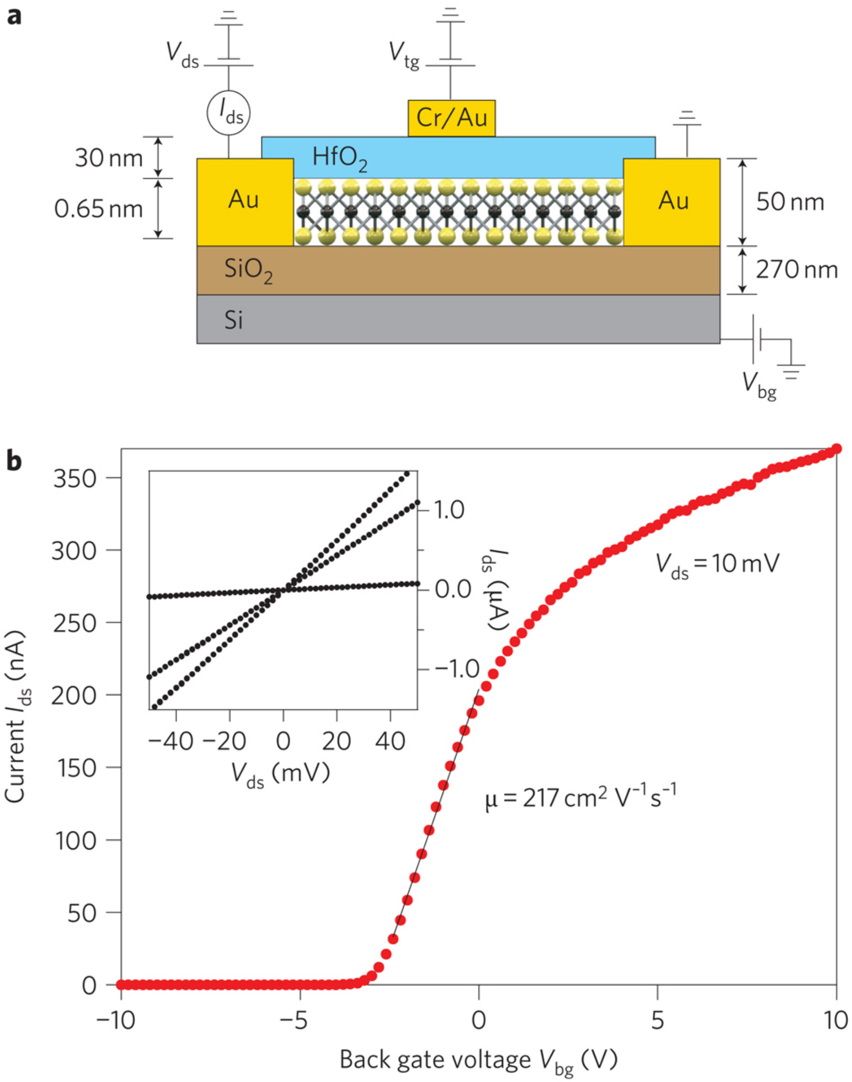
Editorial, Nature Nanotechnology, 7, 683 (2012).

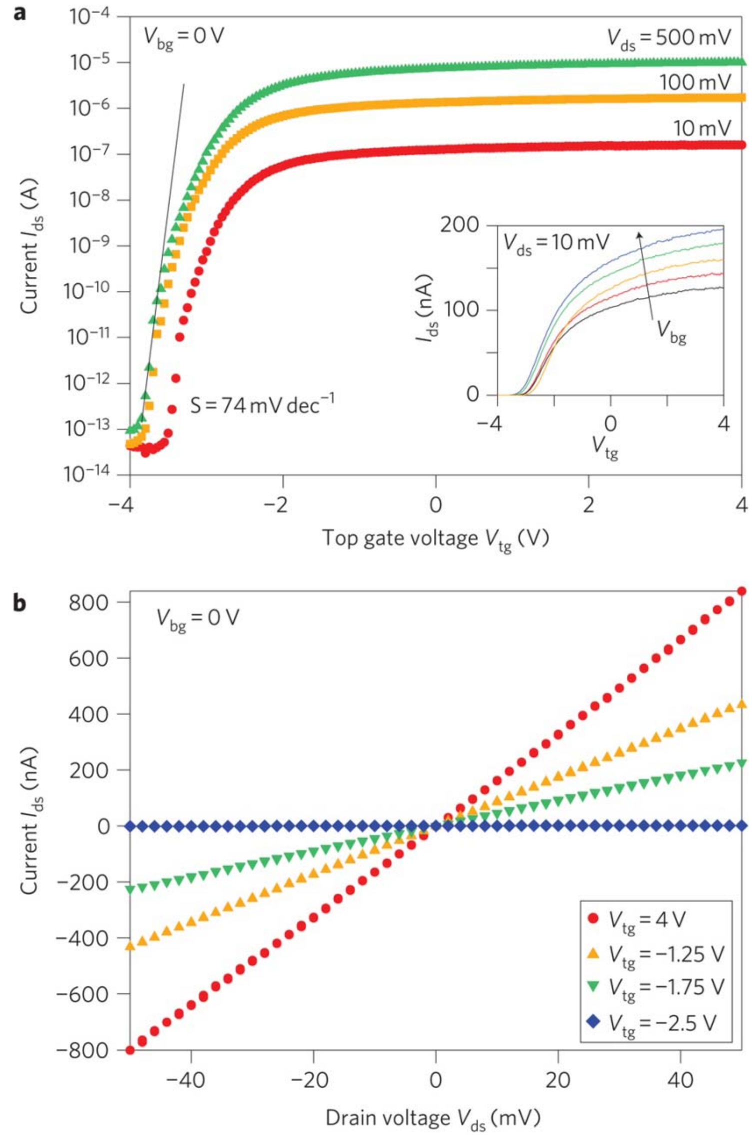
MoS_2



- Poluprovodnik, masivni, en. procep 1,2 eV; nanosloj 1,8 eV
- Pokretljivost u nanoslojnom MoS_2 (Radisvaljević, 2011): 200-2500 $cm^2/(Vs)$
- Temperaturska stabilnost: do oko 1100^oC

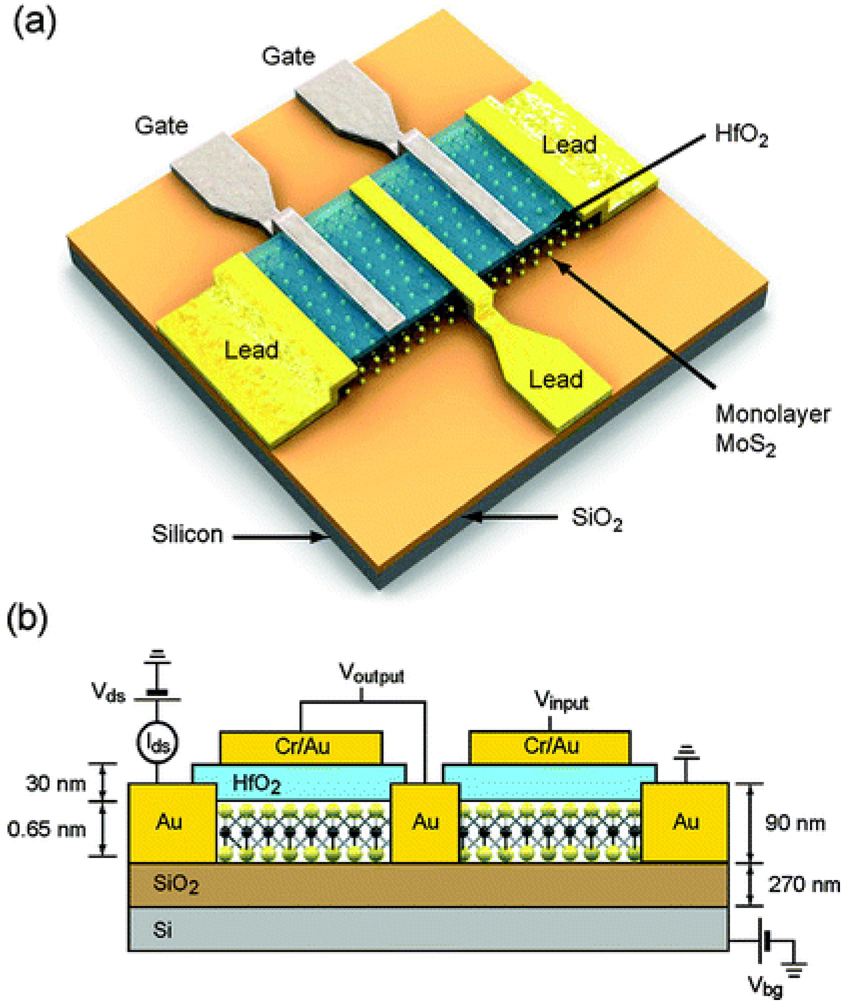
MoS_2 FET

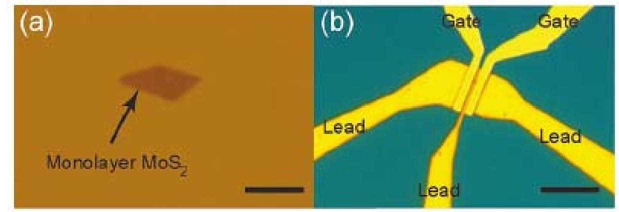


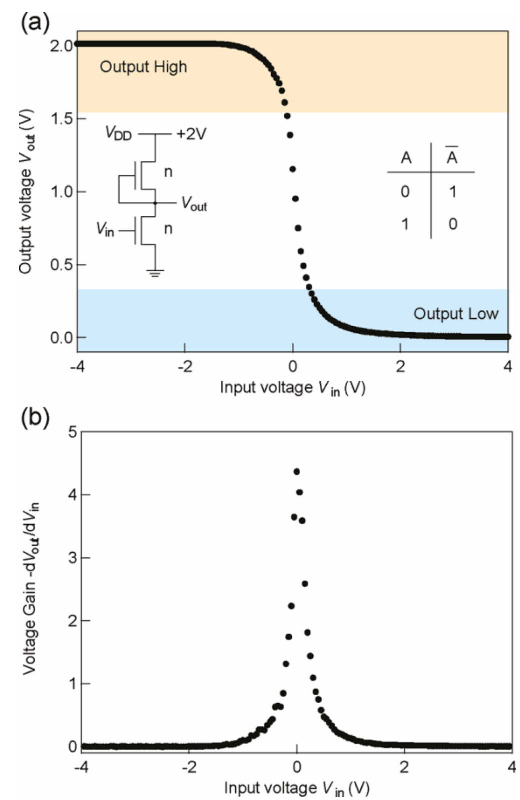


B. Radisavljević et al., Nature Nanotechnology, 6, 147 (2011); 8, 147 (2013)

Prvo MoS_2 integrisano kolo



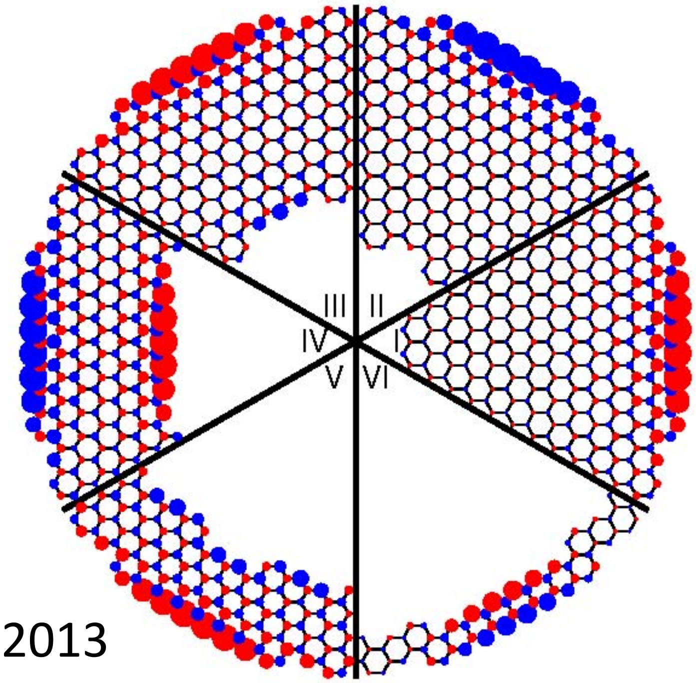




B. Radisavljević et al., ACS Nano, 5, 9934 (2011); 7, 3729 (2013)

Novi efekti i nove funkcionalnosti

- Spintronika
  - magnetizam u grafenskim kvantnim tačkama
    (Grujić, PRB, 2013);
- Topološki izolator
  - topološki izolatori u funkcionalizovanom grafenu
    (Grujić, nepublikovano)
- Kvantno računanje:
  - D-Wave
    (Nature 20. jun 2013)



Grujić, PRB, 2013

Zaključak

- Neizvesna sudbina silicijuma u budućnosti: družiće se intenzivnije sa drugim materijalima; nudi drugima velike vejfere
- Sjajna bliska budućnost MOSFET-a na bazi nanožica; slabost nanožica je precizno pozicioniranje
- Prednost nanoslojeva u odnosu na Si je nepostojanje efekata kratkog kanala
- GFET pati od inherentne slabosti usled nedostatka energetskog procepa
- Moguće primene GFET-a u RF elektronici već od 2020. godine
- Dihalkogenidi prelaznih metala: nove zvezde na horizontu
- MoS_2 tranzistor pokazuje izrazitu prednost u odnosu na GFET zbog postojanja energetskog procepa: dobijene su visoke vrednosti ON/OFF odnosa