Nanotechnológia

Tapasztó Levente

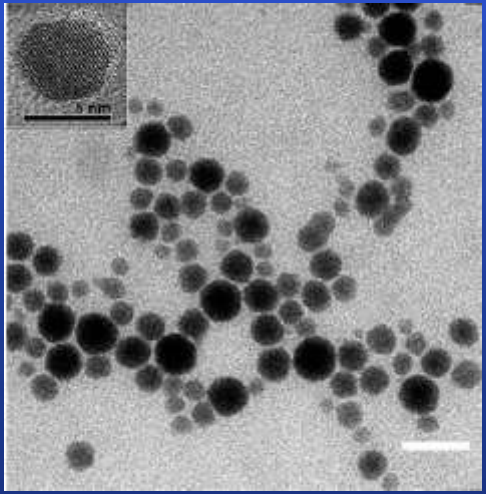
Műszaki Fizikai és Anyagtudományi Kutatóintézet

„There's plenty of room at the bottom"

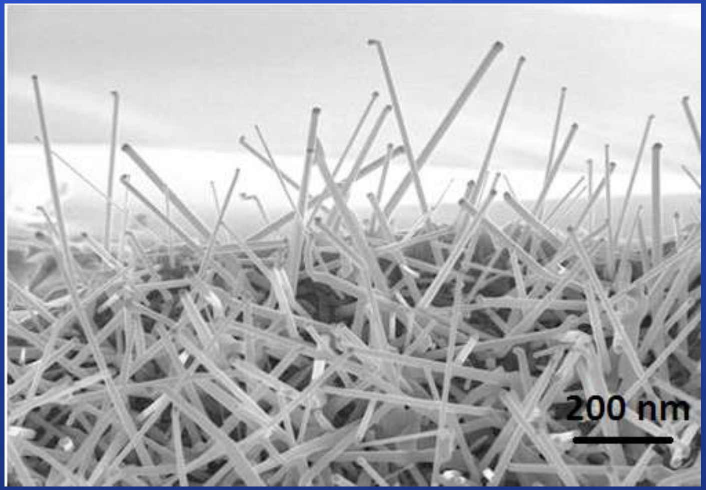
Richard Feymann (1959)

Mi a nanotechnológia?

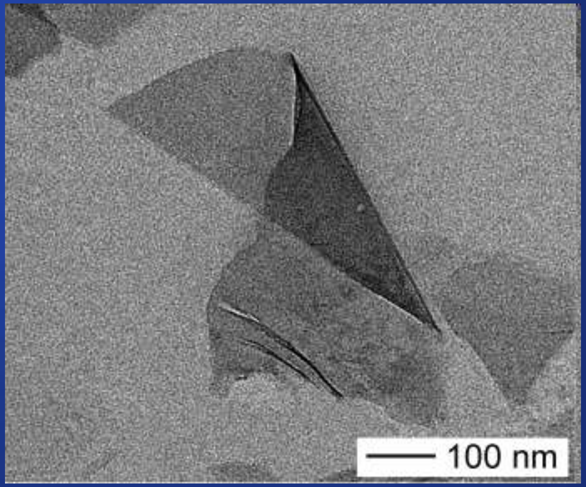
- Olyan szerkezetek (nanoszerkezetek) létrehozása, tanulmányozása és módosítása, amelyek mérete a nanométeres tartományba esik: legalább egyik dimenzióban < 100 nm



Au nanorészecskék



InP nanoszálak



ZnO nanolemezek

Miért érdekes (fontos) a nanotechnológia?

Az anyagok másként viselkednek ebben a mérettartományban:

- megváltoznak az elektromos, optikai, illetve kémiai tulajdonságaik a tömbi viselkedésükhöz viszonyítva pl. Au

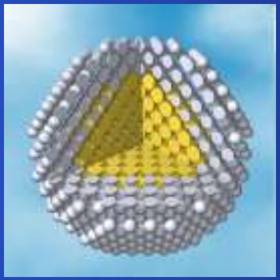
Bulk Gold	Gold as nanoparticles
•Shiny •Always gold in colour •Inert •Conducts electricity	•Varies in appearance depending on size and shape of cluster •Never gold in colour, found in a range of colour •A very good catalyst •Not a metal but a semiconductor

Pusztán a méretük megváltoztatásával kontrollálni tudjuk ezen tulajdonságok változását !

Mi az oka a tulajdonságok megváltozásának?

- felületi atomok arányának drasztikus megnövekedése – kémiai tulajdons.

$$\frac{F_{gomb}}{V_{gomb}} = \frac{4\pi r^2}{\frac{4\pi r^3}{3}} \propto \frac{1}{r}$$



- kvantummechanikai effektusok – fizikai tulajdonságok

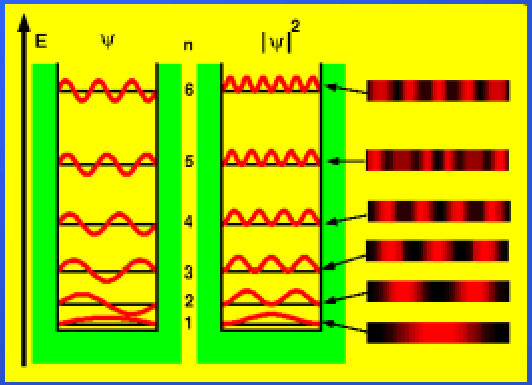
$$p = \frac{h}{\lambda} = \frac{h}{2\pi}k = \hbar k$$

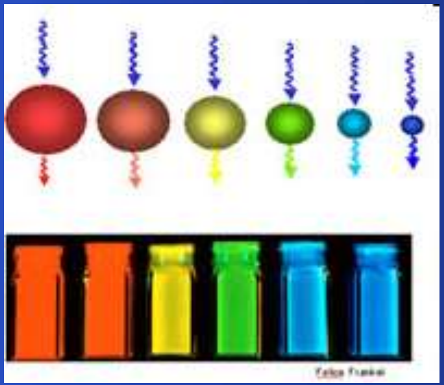
$$\left(\frac{\hat{\boldsymbol{p}}^2}{2m} + V(\boldsymbol{r})\right)\Psi(\boldsymbol{r}) = E\Psi(\boldsymbol{r})$$

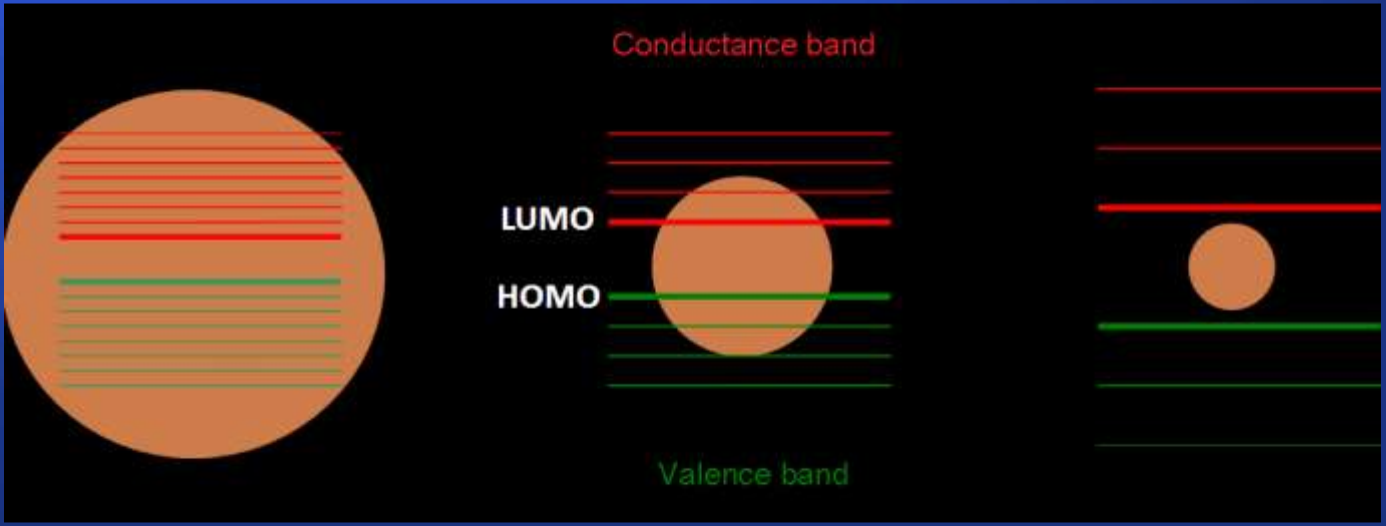
a kristályra jellemző sávszerkezetet felülírják a mérethatások:

– kvantum-bezártság: akkor lép fel ha az elektronok koherenciahossza összemérhető a szerkezet méreteivel – interferencia hatások

Kvantum-méret hatások







a kristályra jellemző sávszerkezetet felülírják a mérethatások

Nanoszerkezetek előállítása

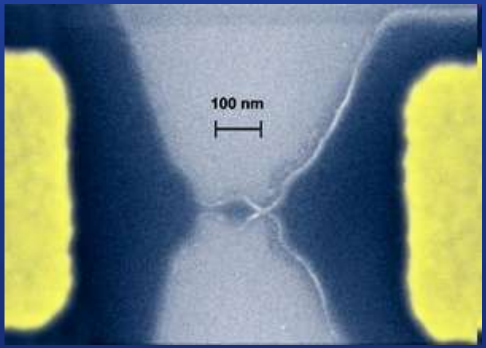
Számos fizikai és kémiai eljárás létezik.

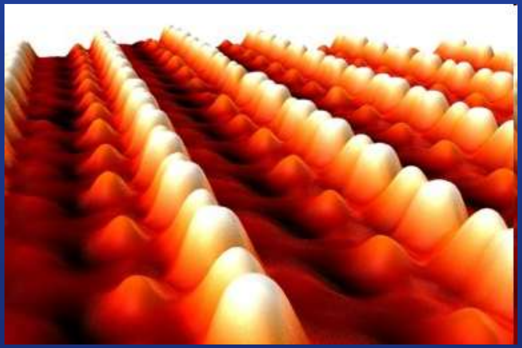
Két alapvető koncepció:

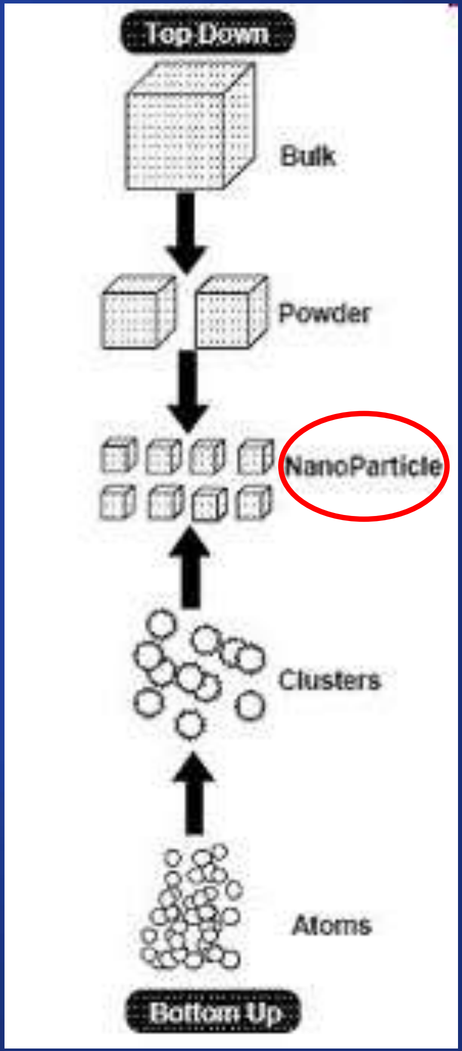
top-down vs. **bottom-up**

- Litográfiás eljárások
- Elektronikus eszközök

- kémiai szintézis
- önszerveződés





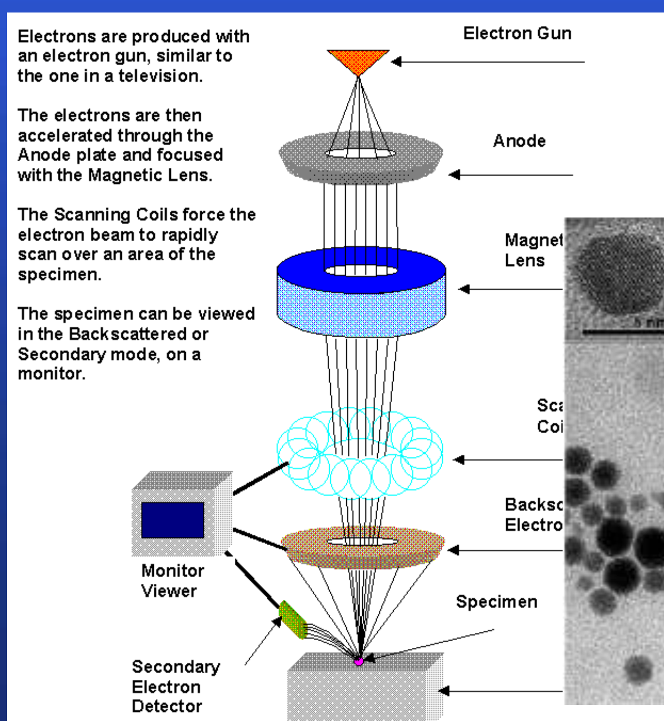


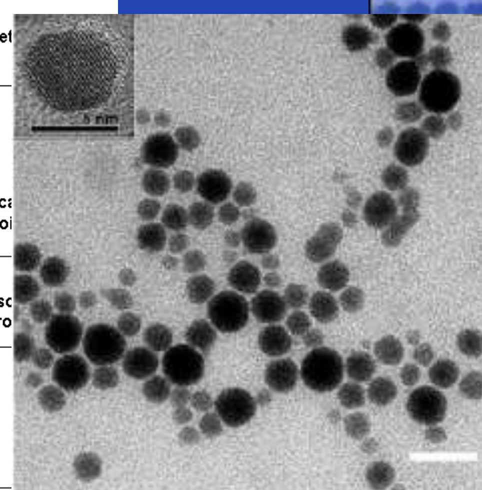
Mivel vizsgálhatjuk a nanoszerkezeteket?

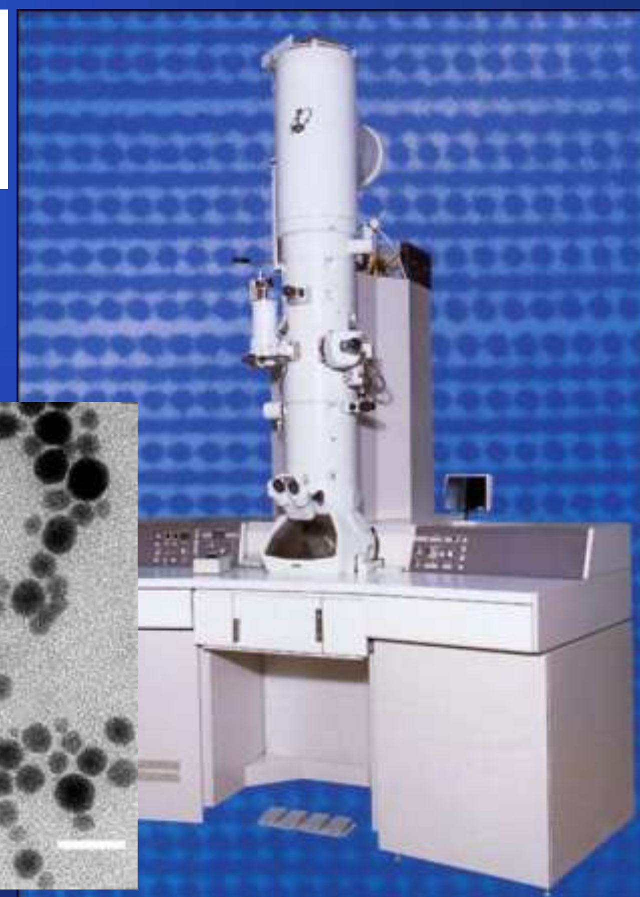
Optikai mikroszkóp: túl nagy a látható fény hullámhossza

Megoldás: Elektronmikroszkóp

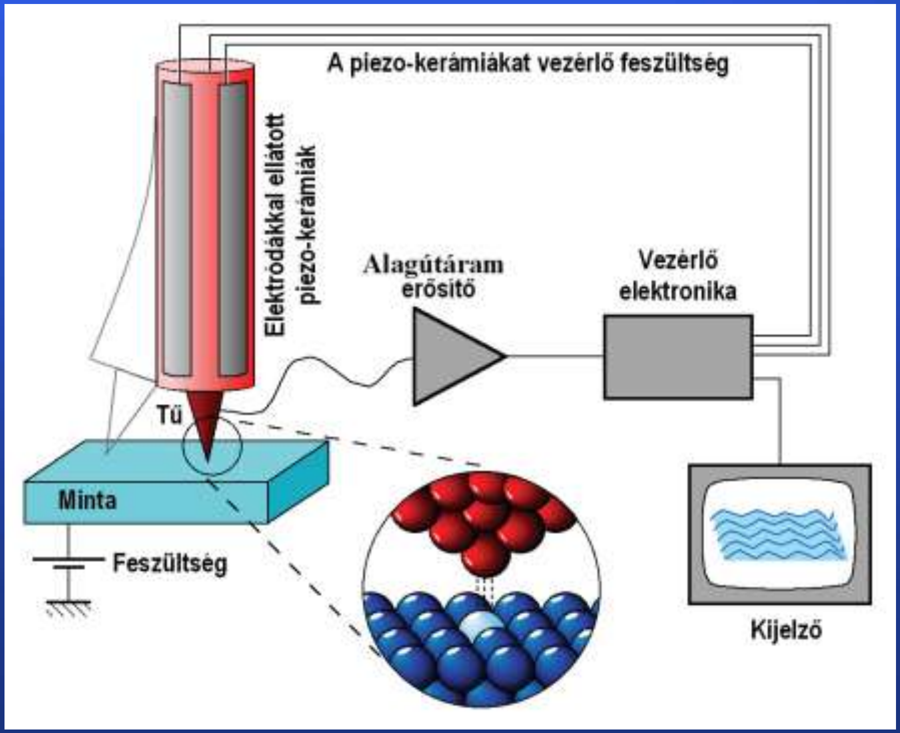
$$E = \frac{hc}{\lambda}$$

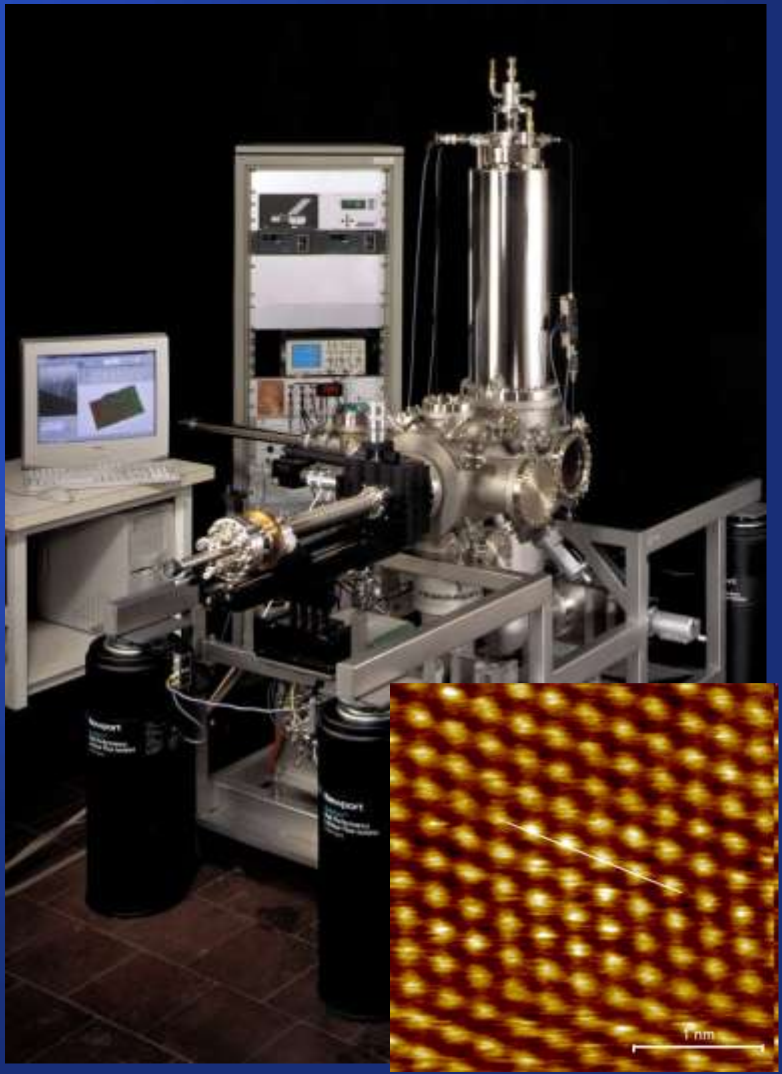




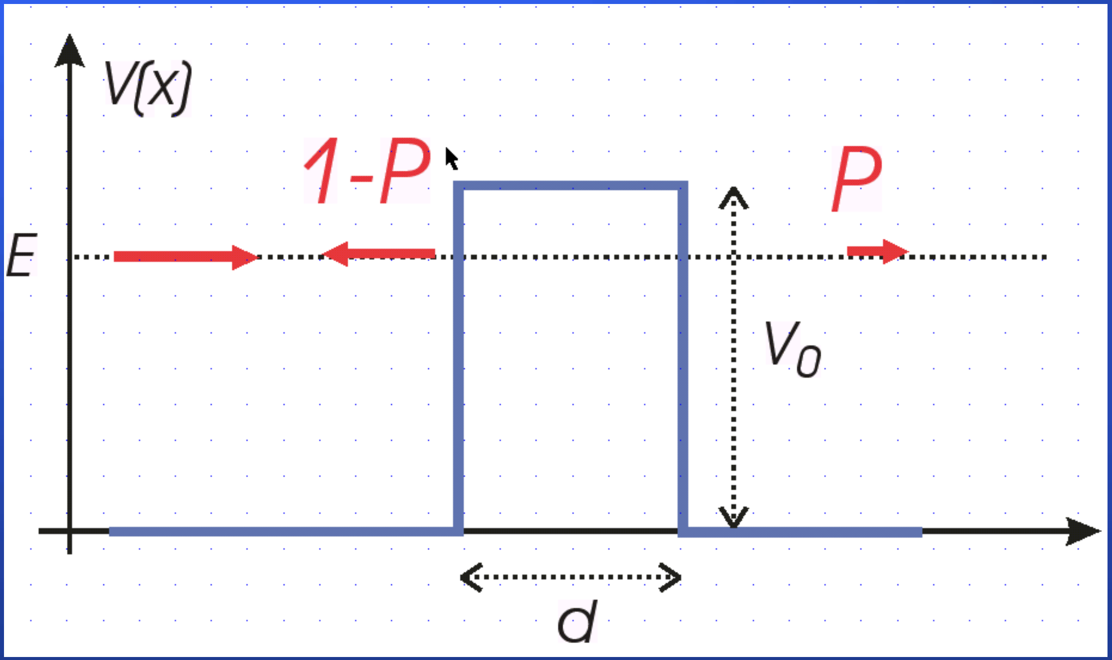


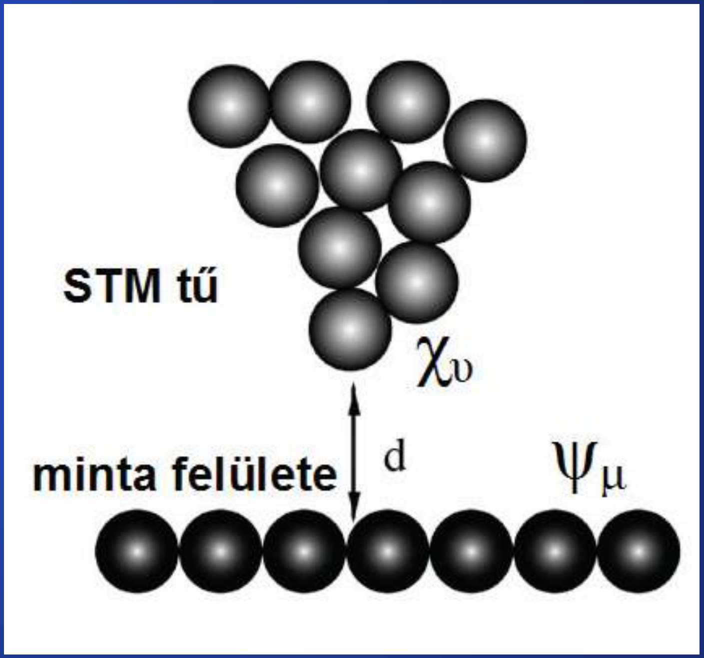
Pásztázó alagútmikroszkóp - STM





Kvantummechanikai alagutazás



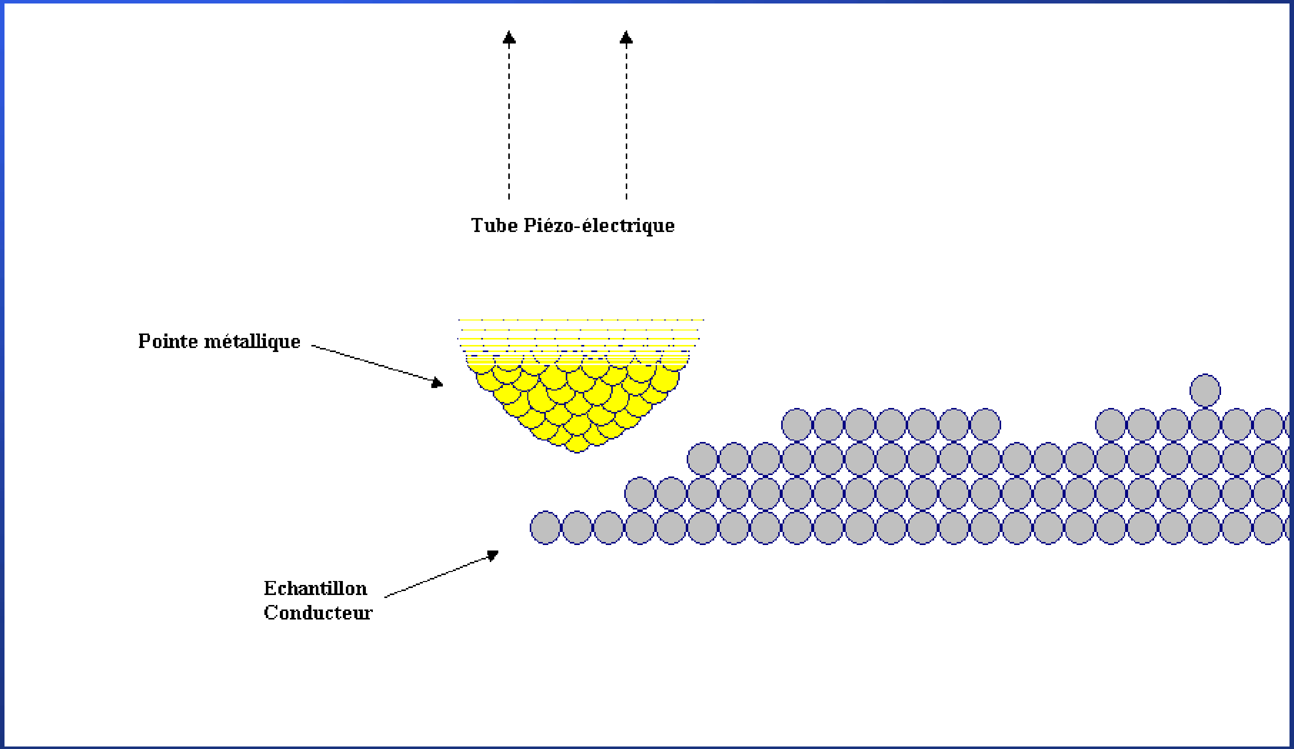


$$P \propto e^{-2\kappa d}$$

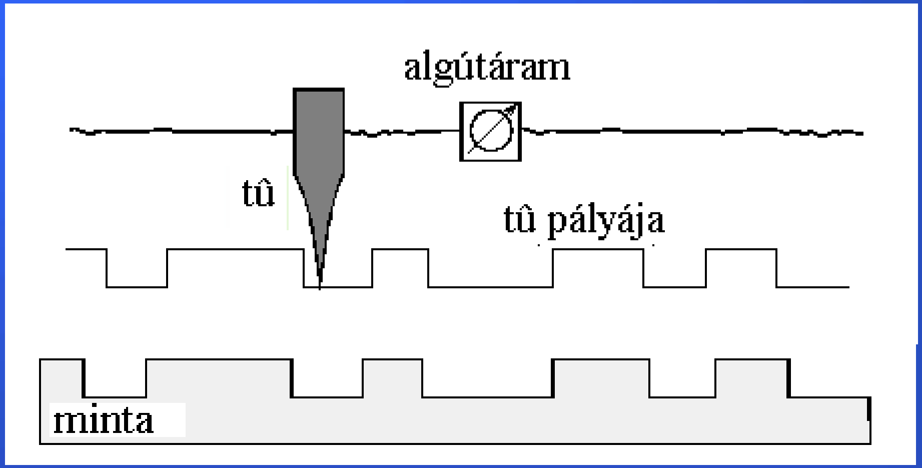
$$\kappa = \sqrt{2m/\hbar^2 \, (V_0 - E)}.$$

$$I \propto \exp(-2\kappa d)$$

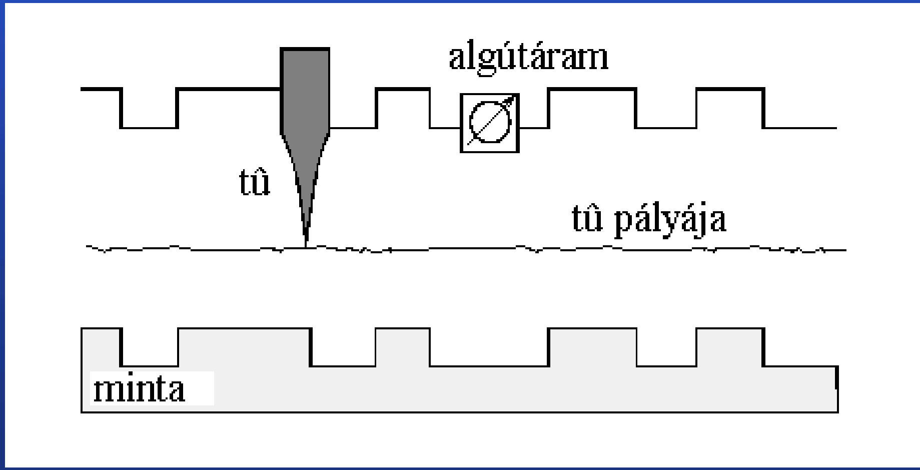
STM animáció



STM üzemmódok



1) I_t = állandó (topográfiai üzemmód)

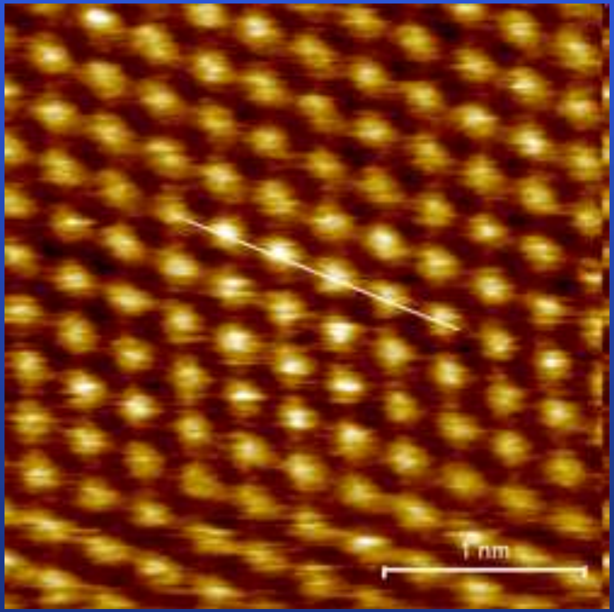


2) d = állandó (állandó "magasság" üzemmód)

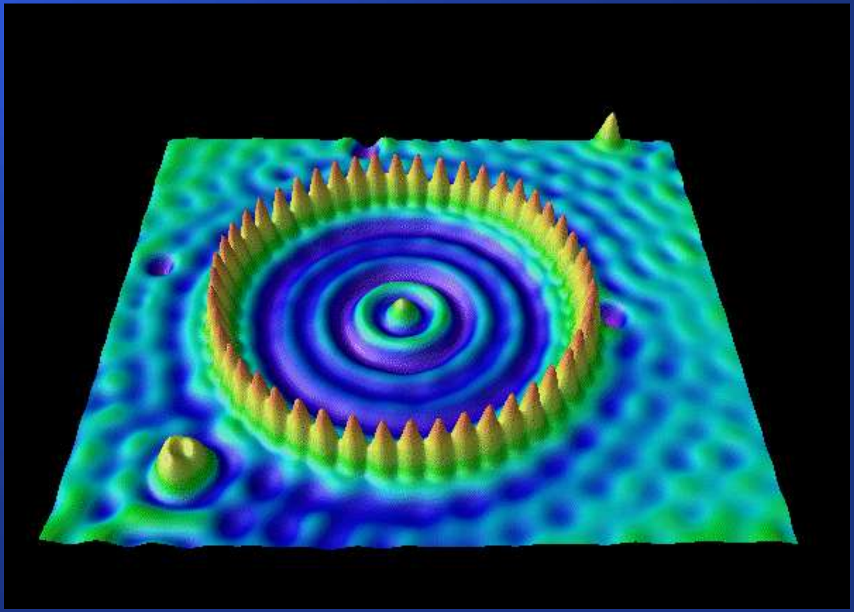
STM elmélet

$$I_t = 2\frac{\pi e}{\hbar}\sum_{\mu,\nu}\left|\left\langle \chi_\nu \left| V_{tunel} \right| \psi_\mu \right\rangle\right|^2 \delta\left(E_\mu + eV_t - E_\nu\right)$$

$$I(\vec{r}) \propto \int_{E_F - eU_{bias}}^{E_F} \rho_{LDOS}(\vec{r}, E)$$

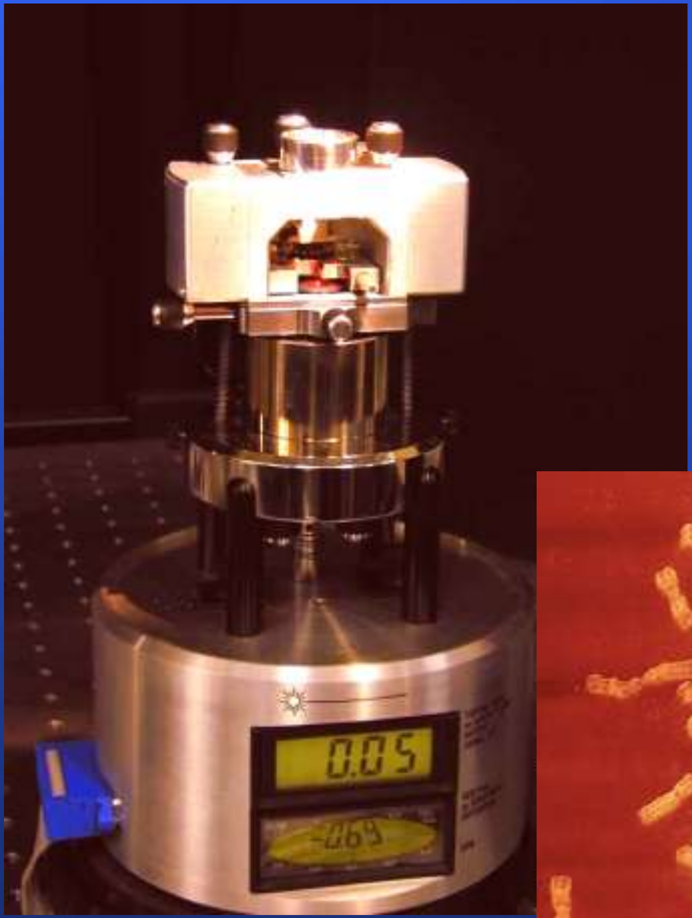


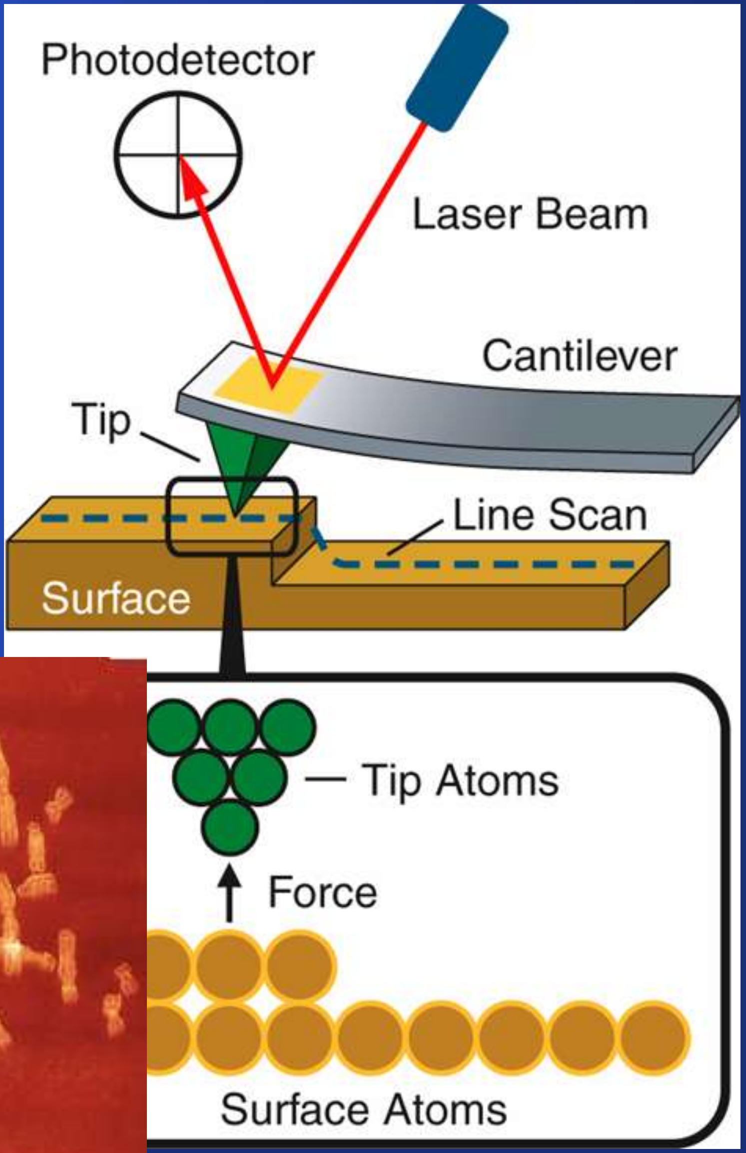
Atomi szerkezet



Elektronszerkezeti hatások

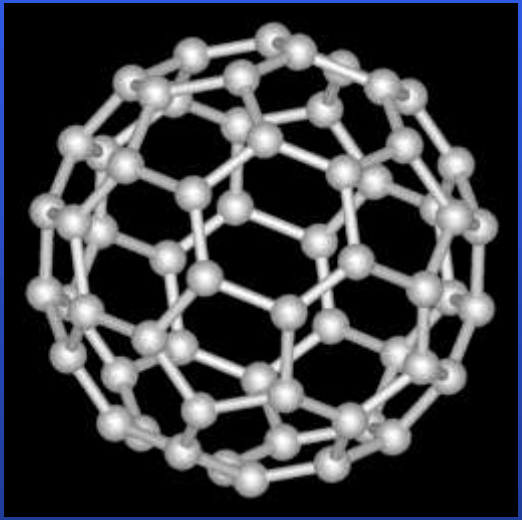
Atomerő mikroszkóp





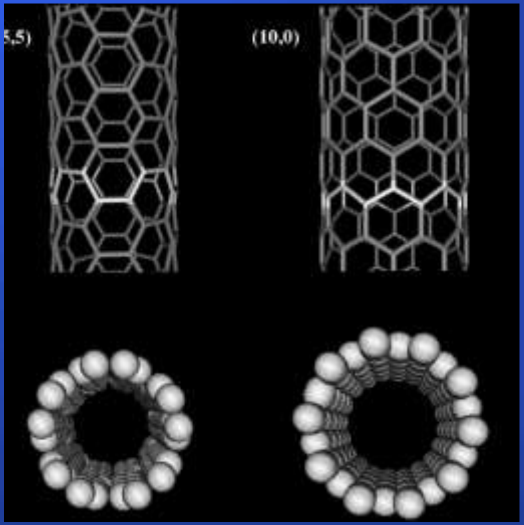
Szén nanoszerkezetek

Fullerén
0D



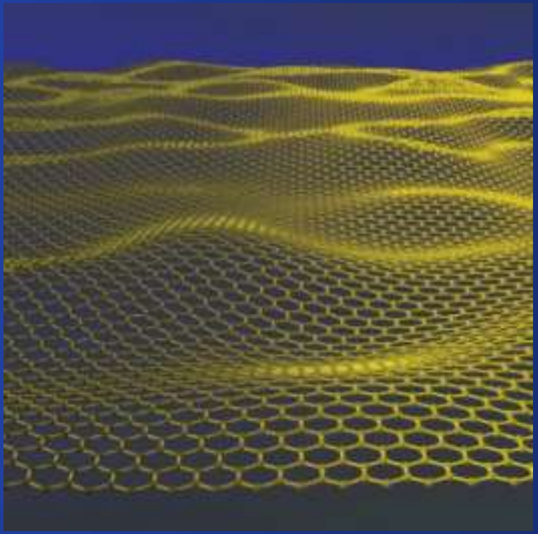
1985
H.W.Kroto

Nanocső
1D



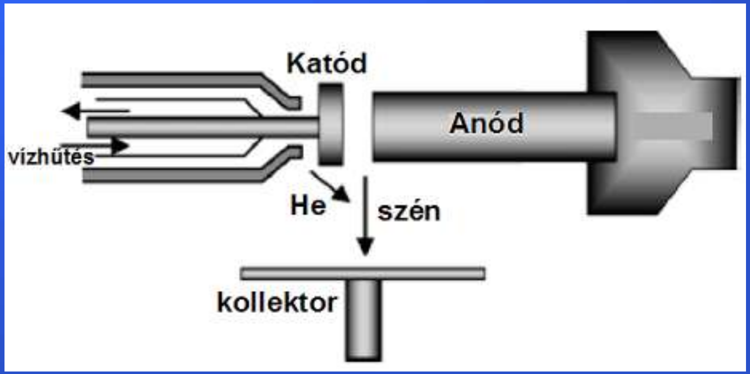
1991
S Iijima

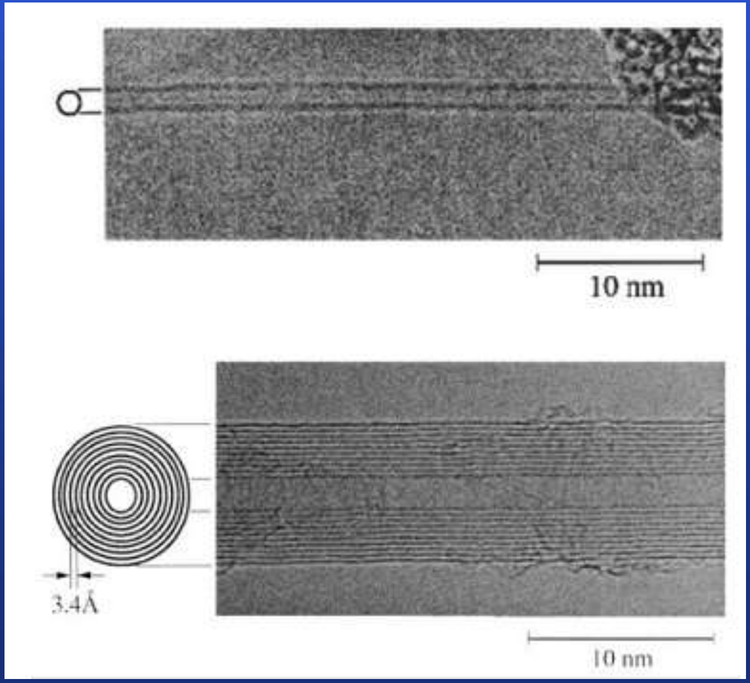
Grafén
2D



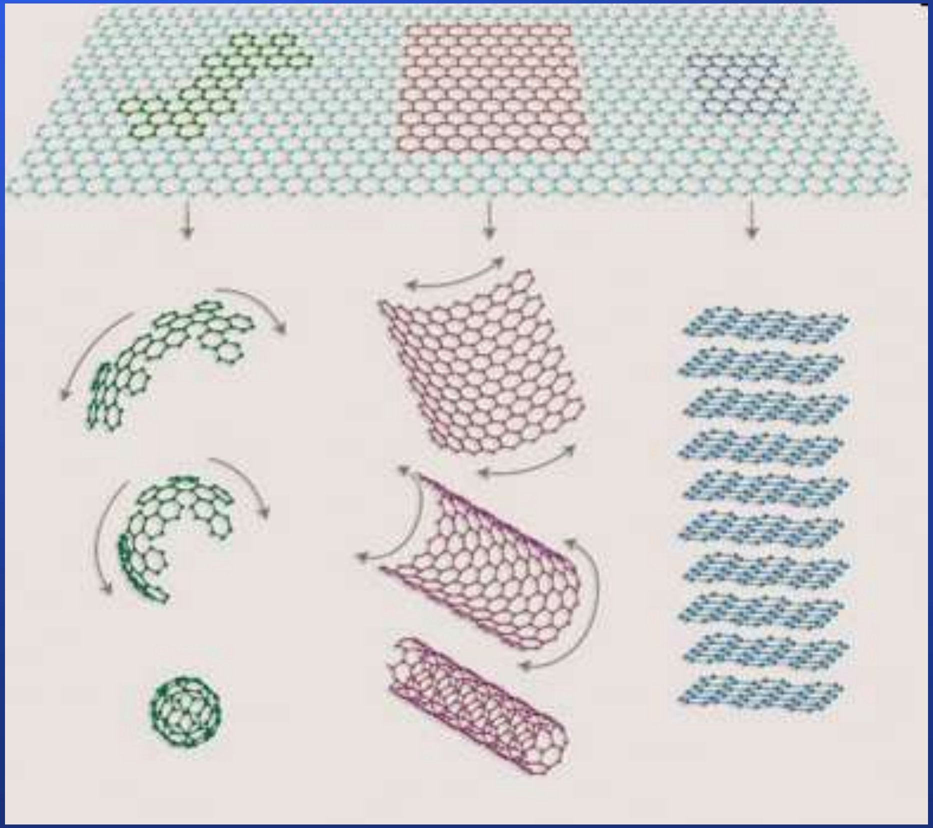
2004
K. S. Novoselov

Nanocsövek felfedezése

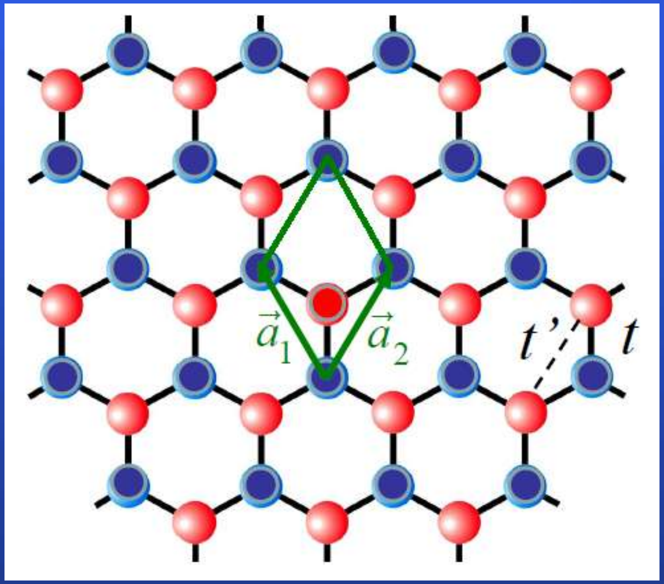


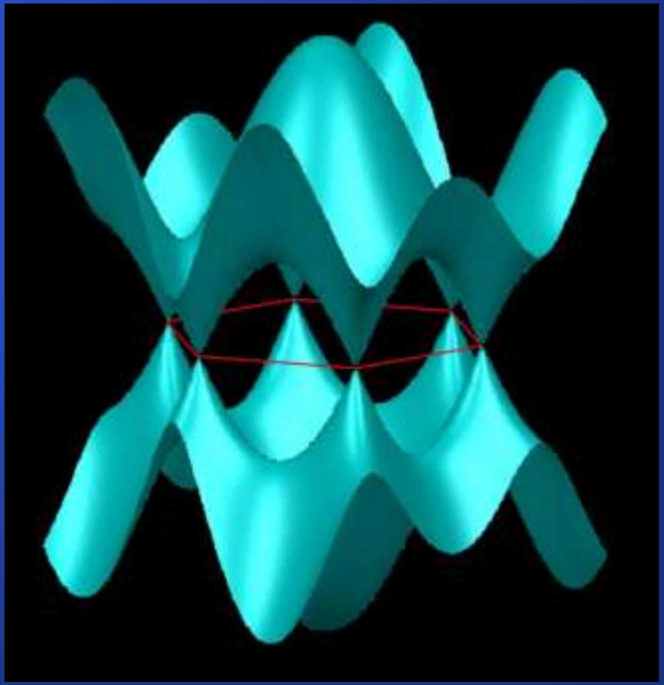


Kiindulópont: a grafén elektronszerkezete



A grafén elektronszerkezete

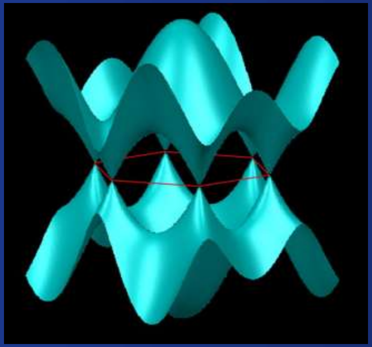




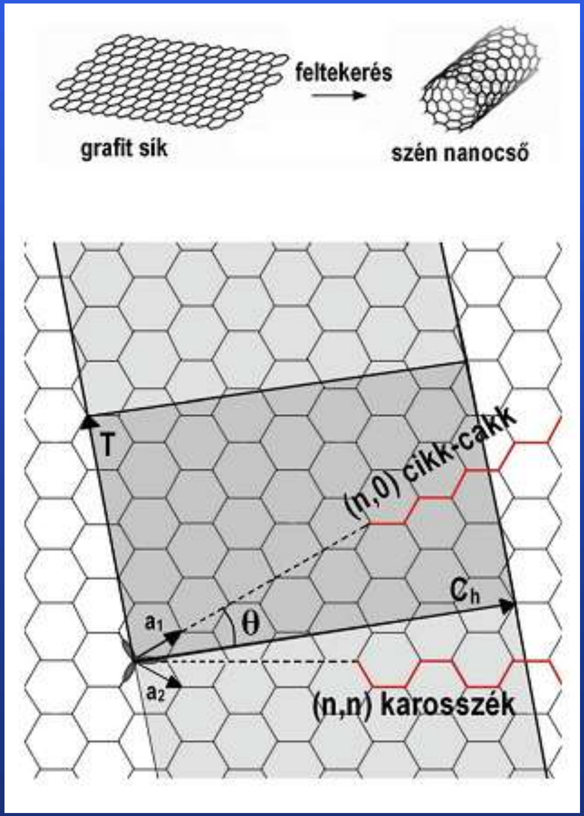
$$E_{2D}(\vec{k}) = \frac{\varepsilon_{2p} \pm \gamma_0 w(\vec{k})}{1 \pm s w(\vec{k})}$$

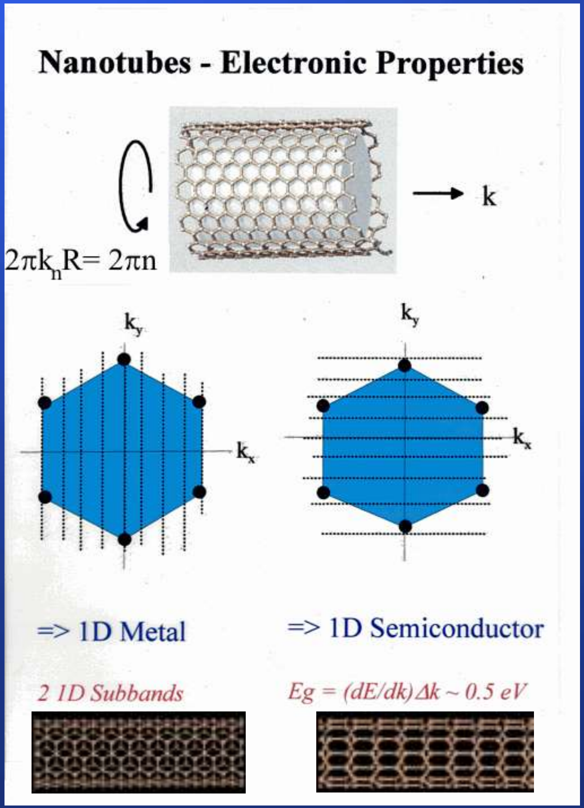
$$w(\vec{k}) = \sqrt{\left|f(\vec{k})\right|^2} = \sqrt{1 + 4\cos\frac{\sqrt{3}k_x a}{2}\cos\frac{k_y a}{2} + 4\cos^2\frac{k_y a}{2}}$$

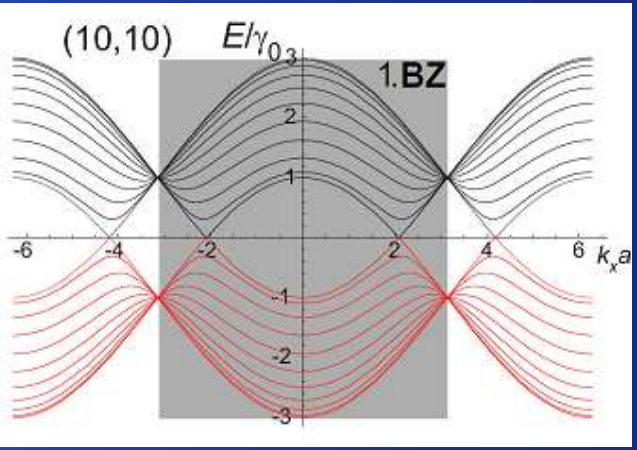
Szén nanocsövek elektronszerkezete

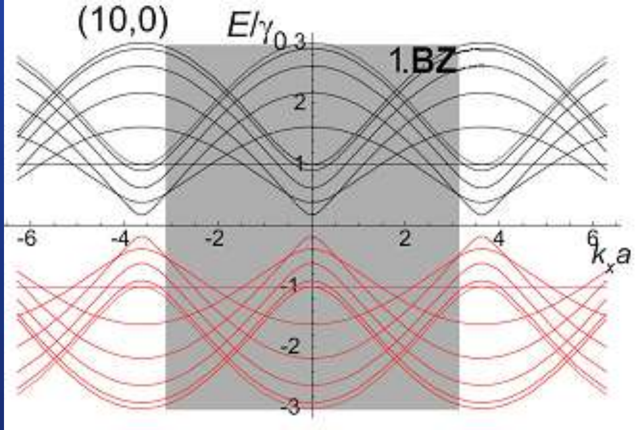


$$\vec{C}_h \vec{k} = 2n\pi$$

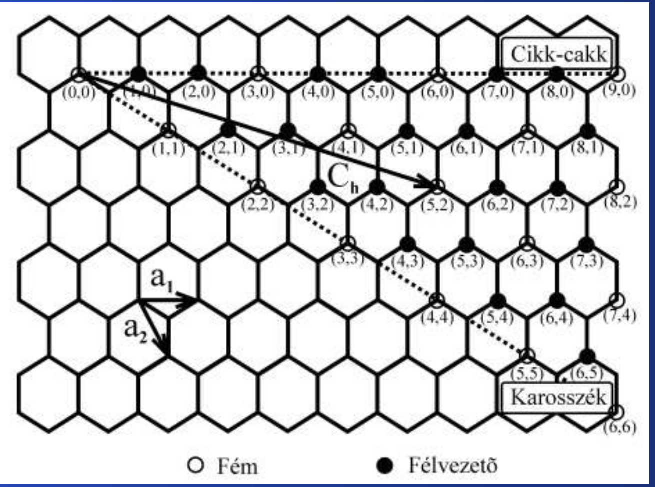


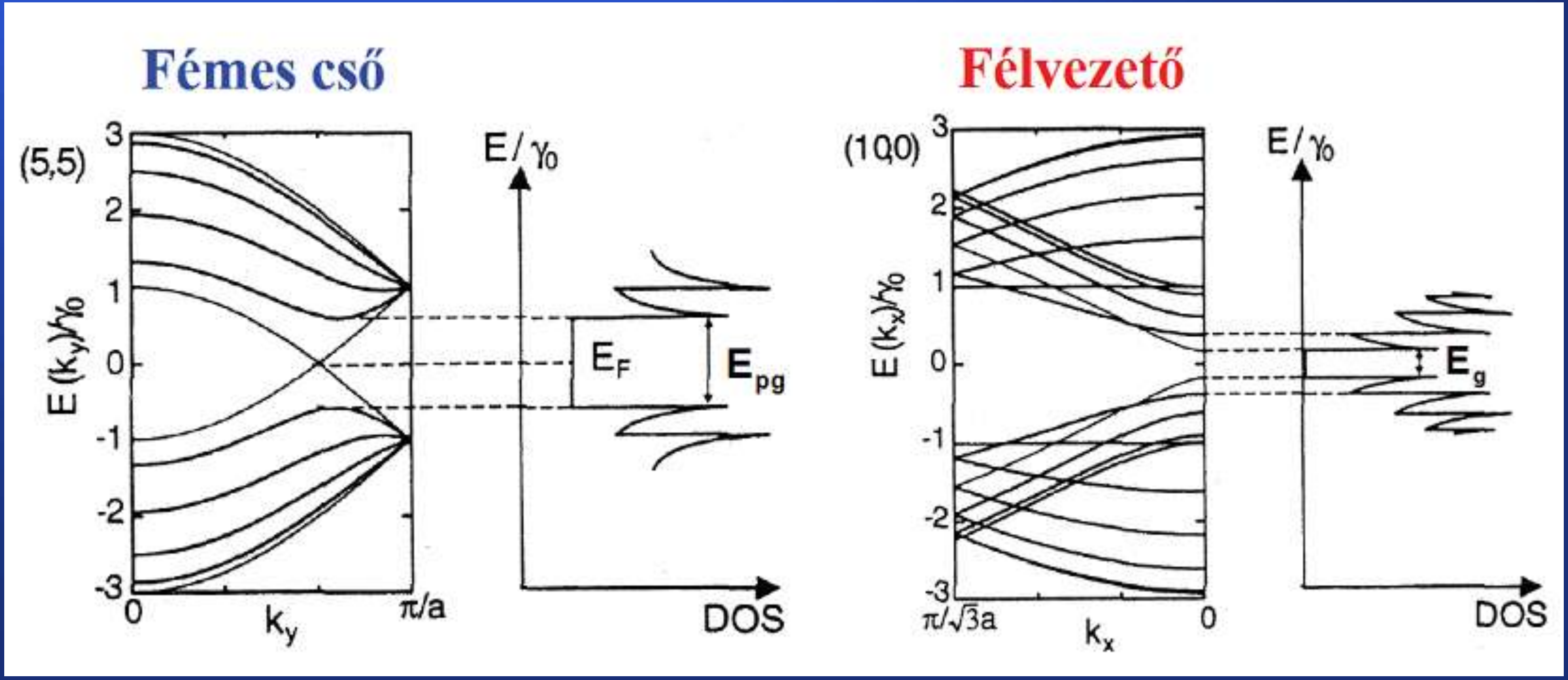




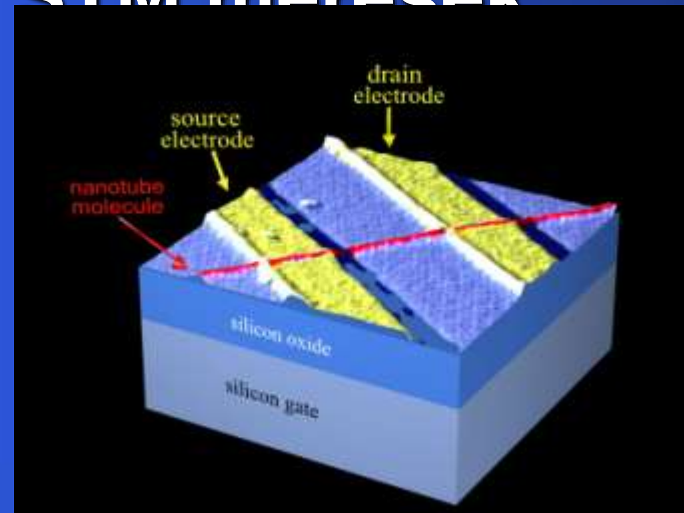


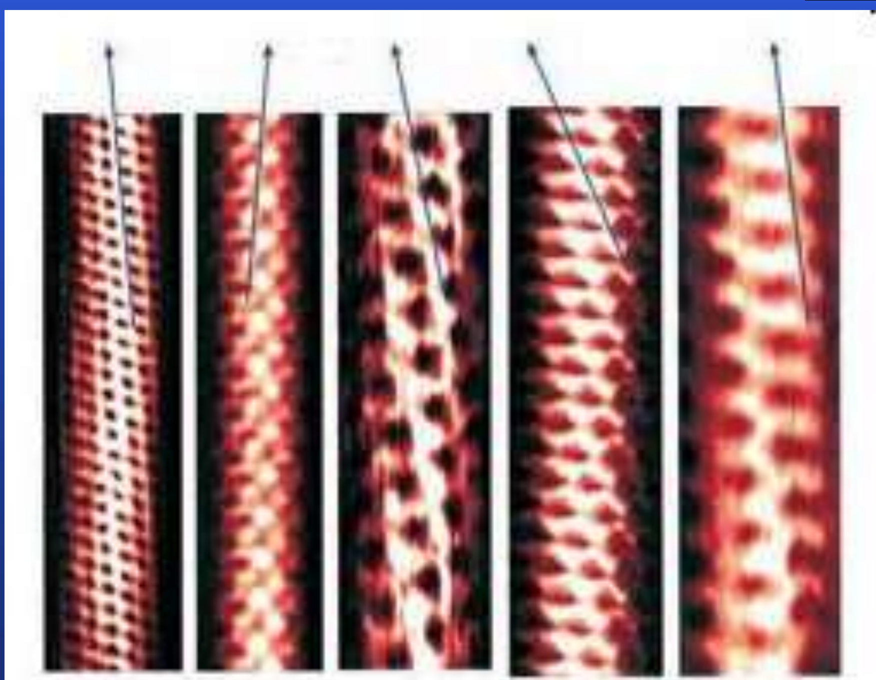
Fémes vs félvezető nanocsövek

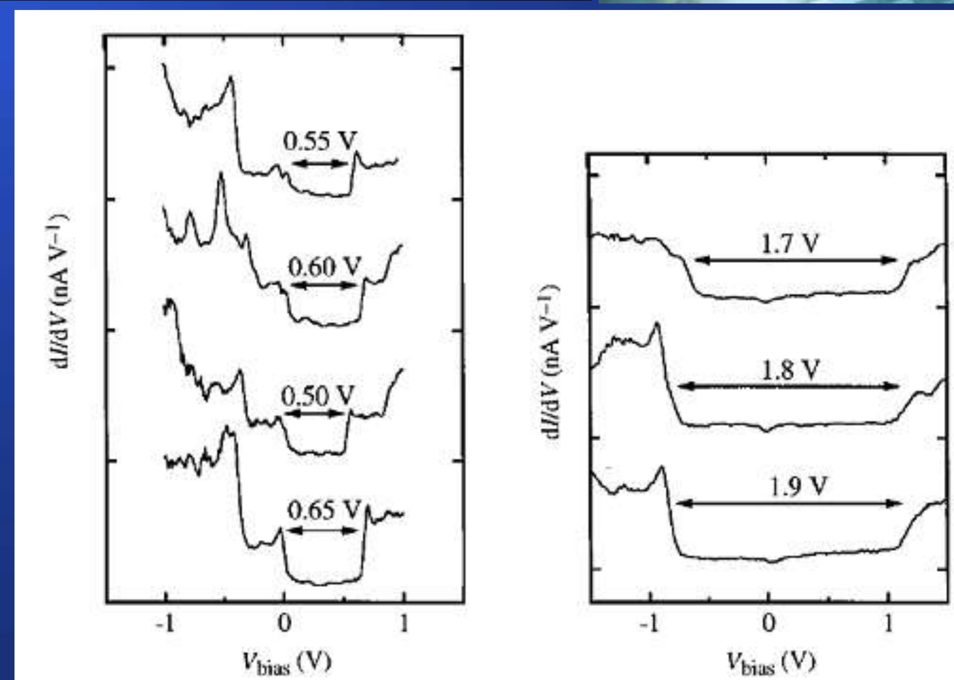




Kísérleti igazolás – STM mérések







Grafén – fizikai Nobel-díj 2010

Andre Geim **Kostya Novoselov**

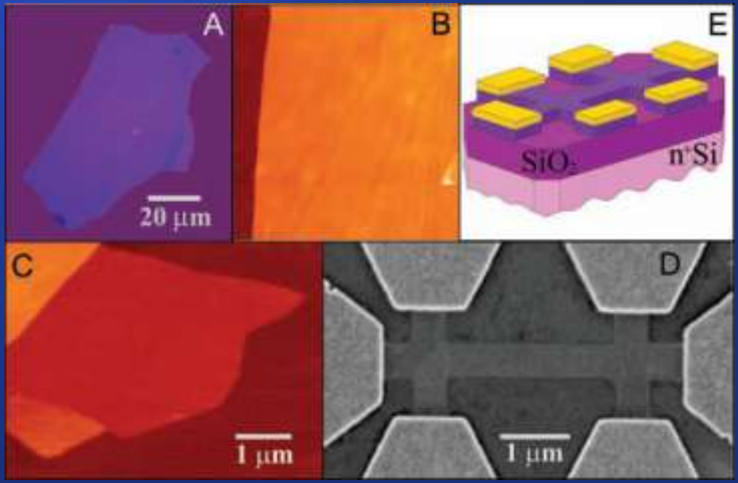
***"**for groundbreaking experiments regarding the two dimensional material graphene"*

Electric Field Effect in Atomically Thin Carbon Films

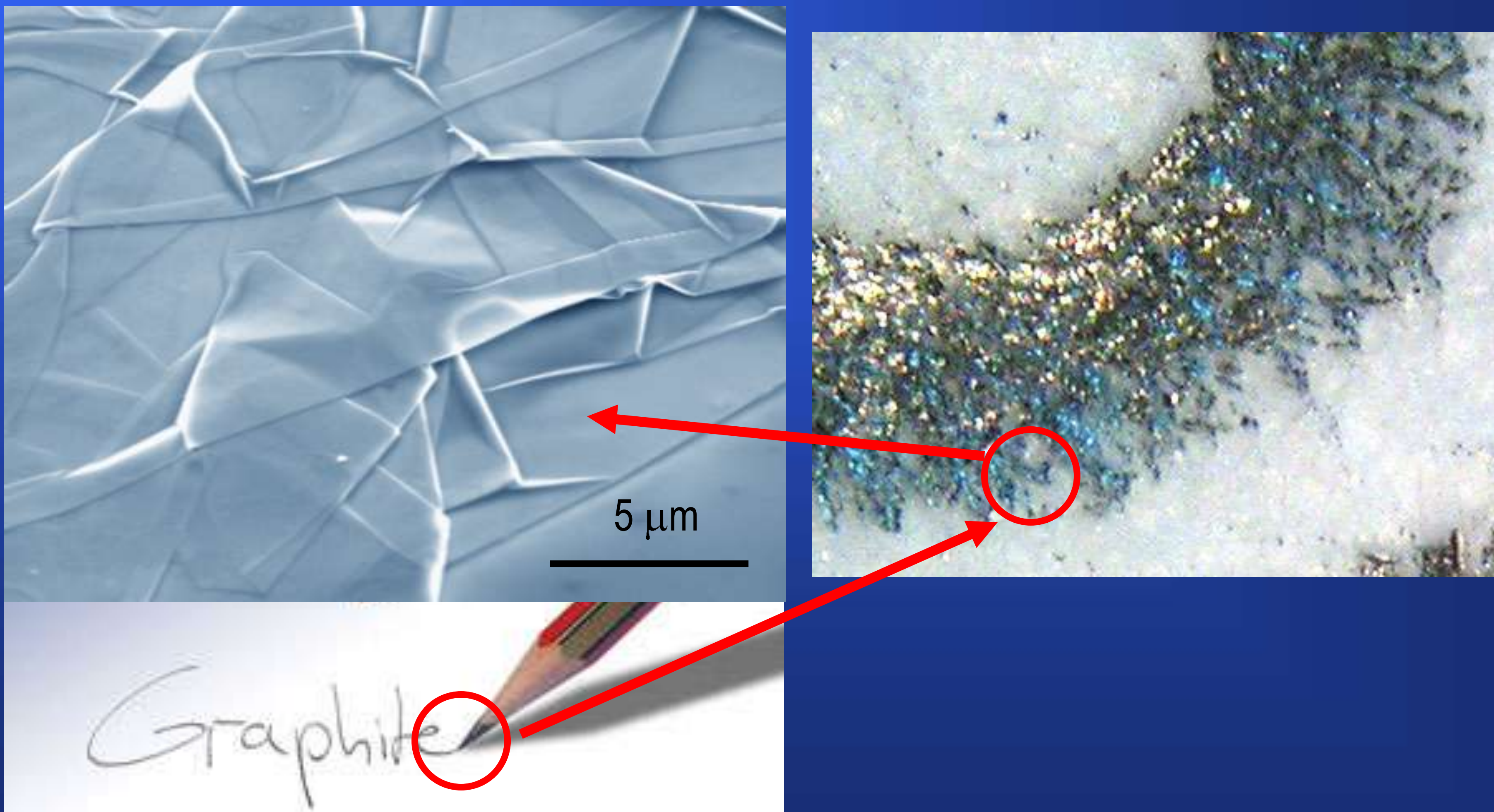
K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

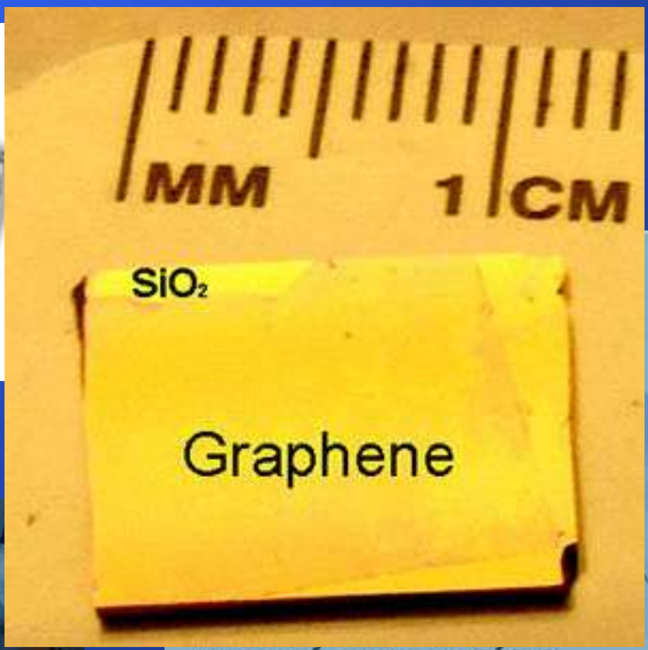
22 OCTOBER 2004 VOL 306 SCIENCE www.sciencemag.org

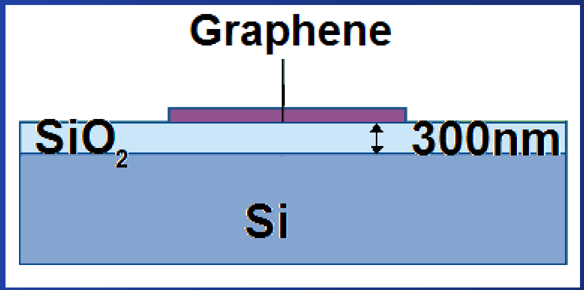


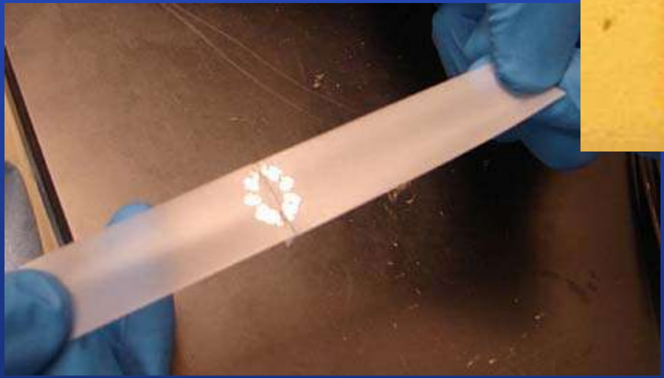
Hogyan állítjuk elő?

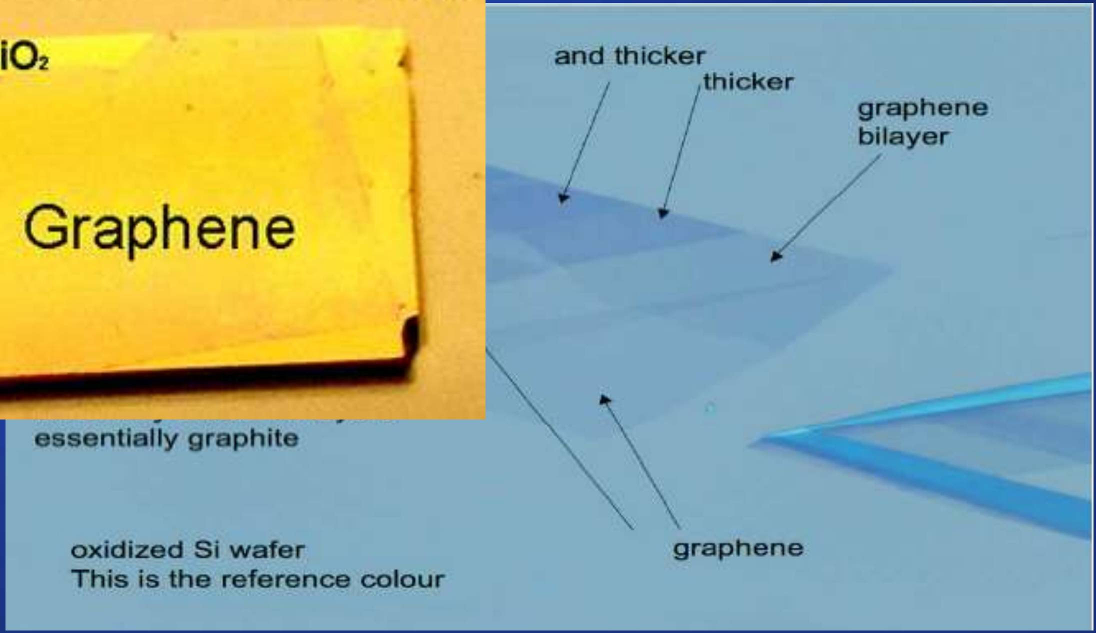


Hogyan azonosítjuk ?





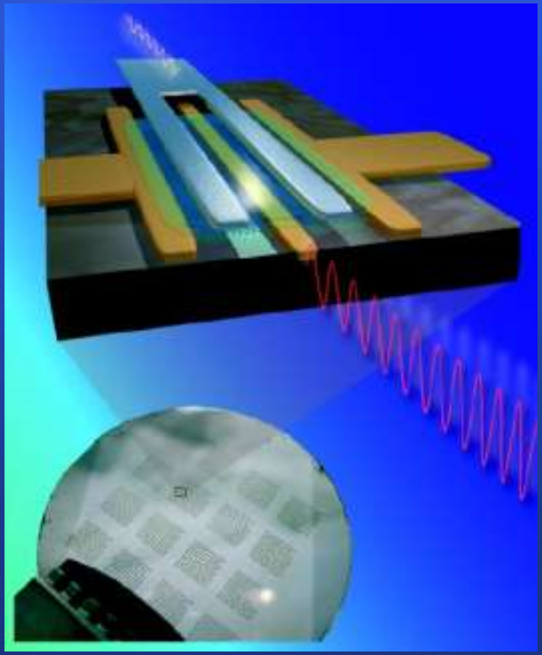




Tulajdonságai

Elektromos tulajdosnágok:

- töltéshordozók mobilitása > 200000 cm²/Vs (Si: <1500 cm²/Vs)
- disszipáció-mentes transzport mikronos távolságokon



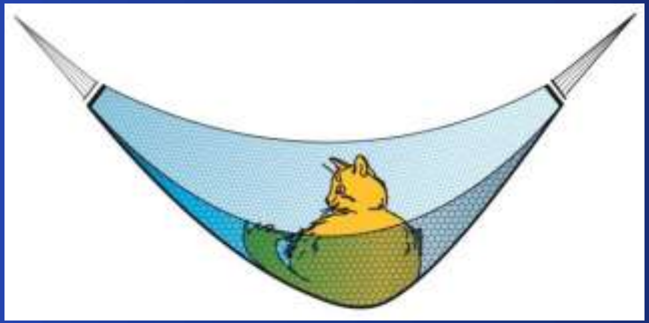
tranzisztor @ 300 GHz

Nature **467**, 305 (2010)

flexibilis, átlátszó elektronika

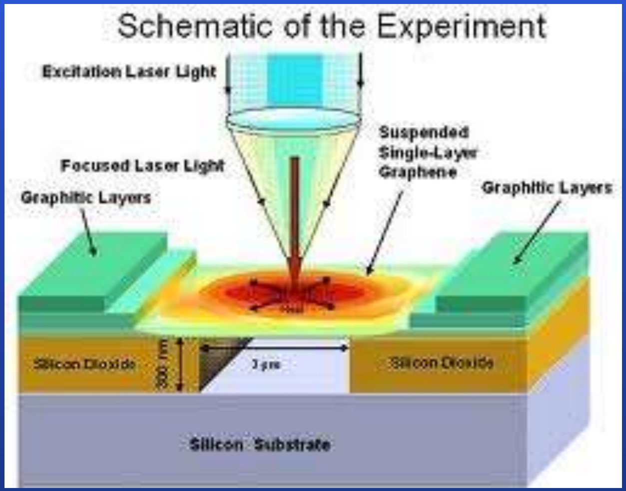
Nature **457**, 706 (2009)

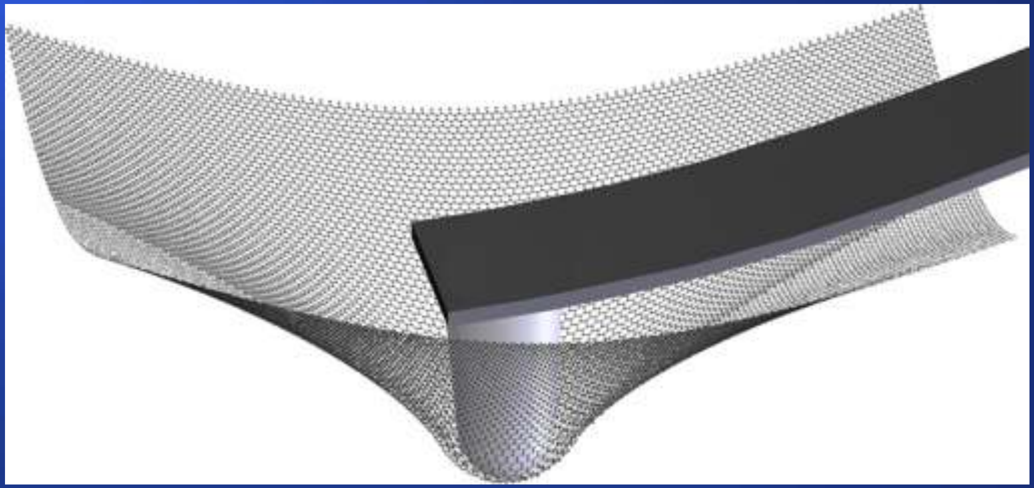
Termális és mechanikai tulajdonságai



Hővezetési együttható 5000 $Wm^{-1}K^{-1}$
(réz 400 $Wm^{-1}K^{-1}$)

Science **321**, 385 (2008)





Nano Lett. **8**, 902 (2008)

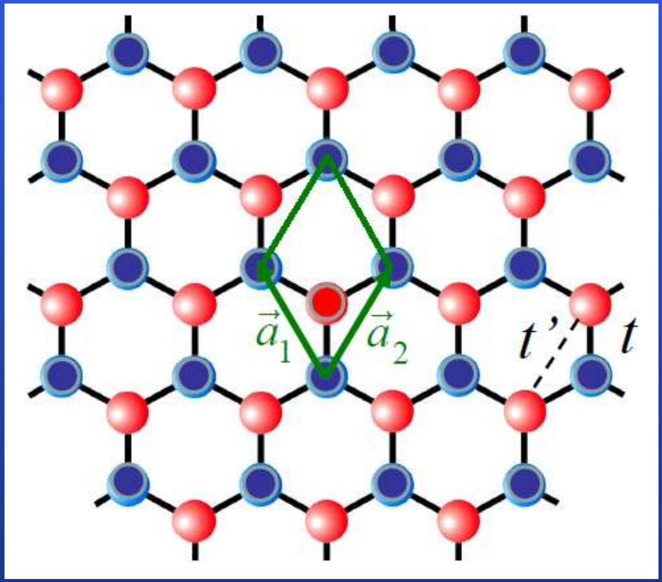
„legerősebb” anayag

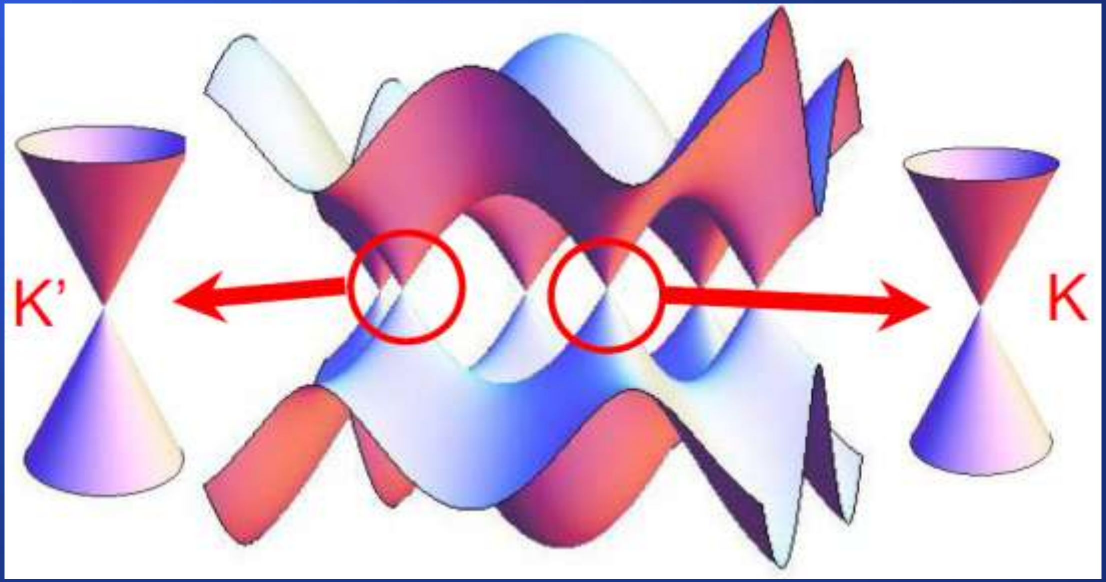
$\rho = 0.77$ mg/m^2

A grafén fizikája

- **nulla tiltott sávú félvezető**

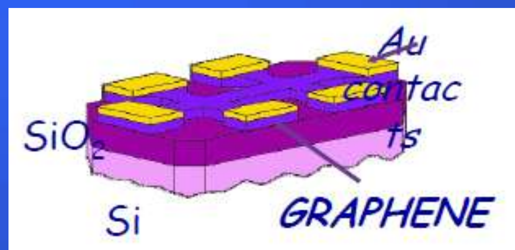
Phys. Rev. 71, 622 (1947)

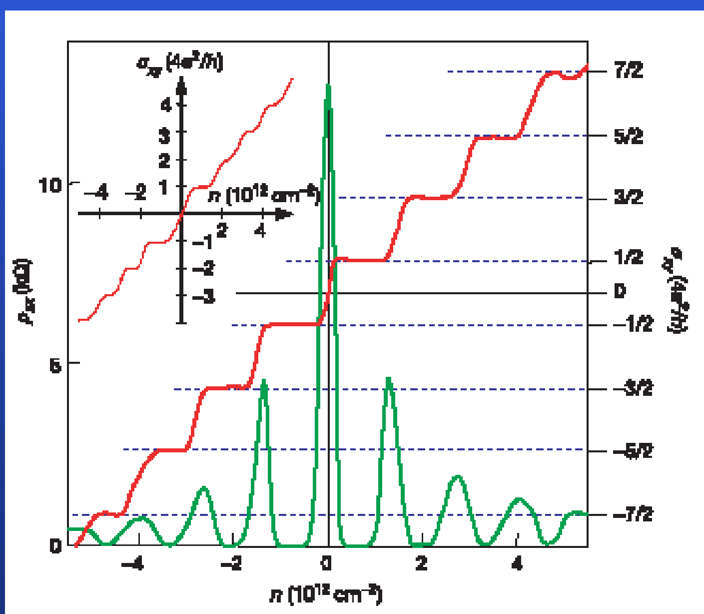


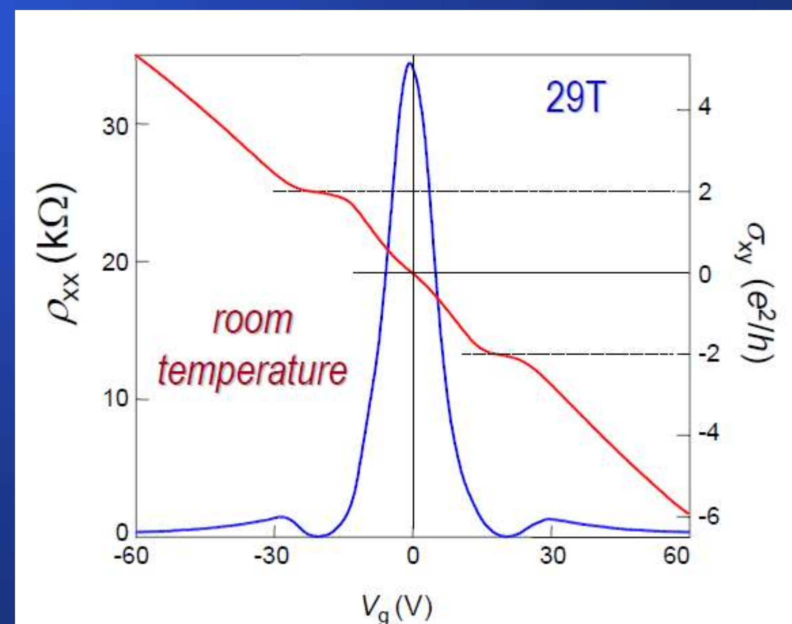


Lineáris diszperzió a Fermi szint közelében – zérus tömegű töltéshordozók - QED

Kísérleti ellenőrzés – Kvantum Hall effektus







Nature 438, 197 (2005)

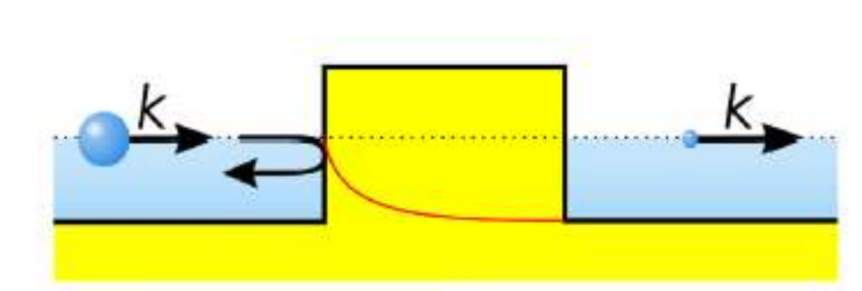
Science 315, 1379 (2007)

A Klein paradoxon

Relativisztikus jelenségek tanulmányozása laborban

Kvantum mechanika

T << 1



Kvantum elektrodinamika

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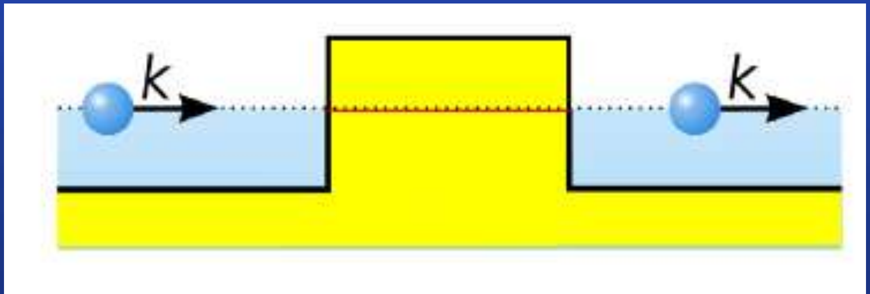
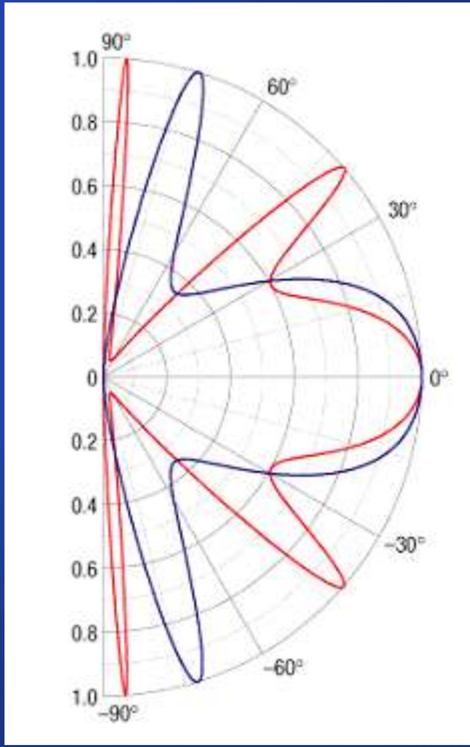
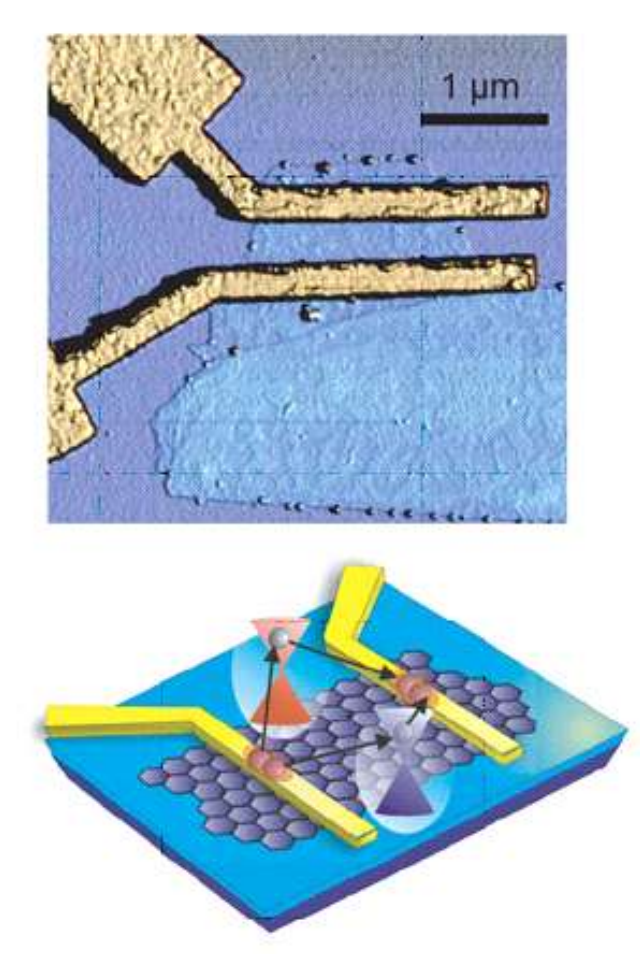
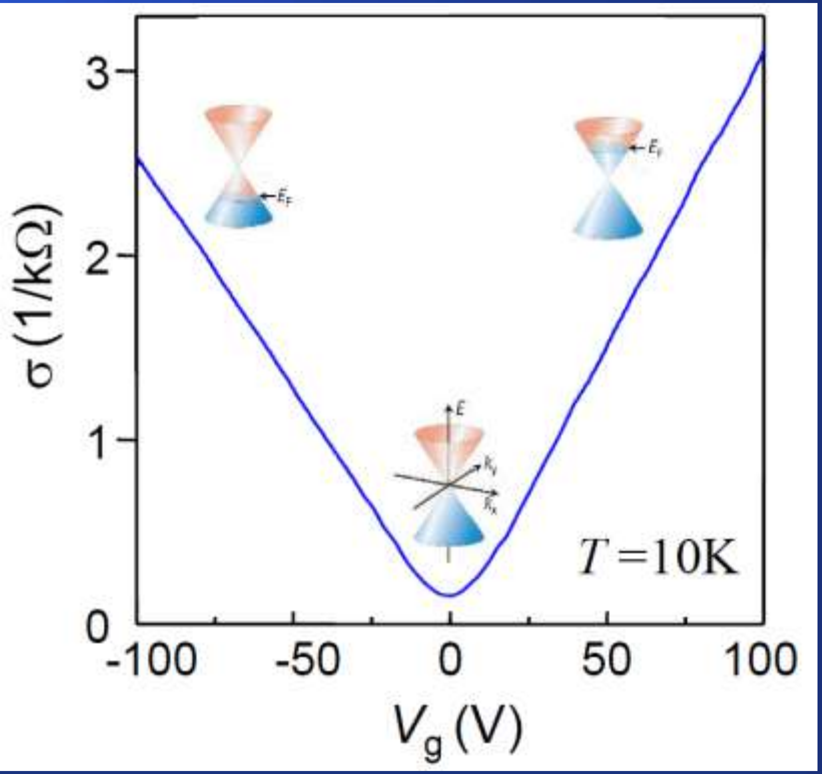




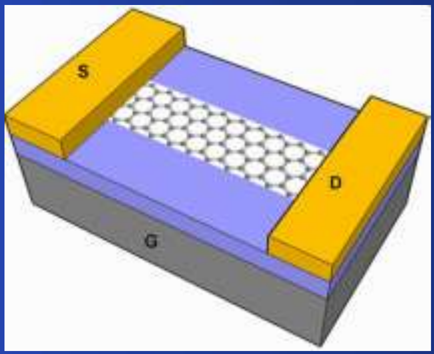
A grafén vezetőképessége

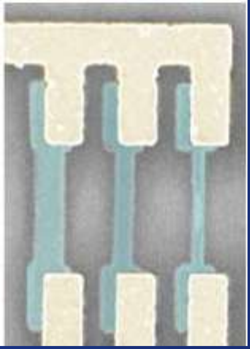




Grafén nanoszerkezetek

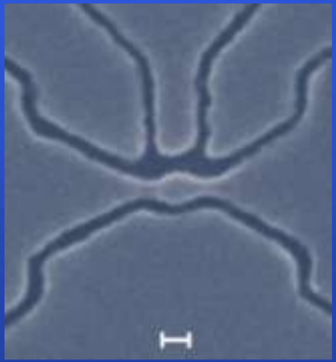
FET

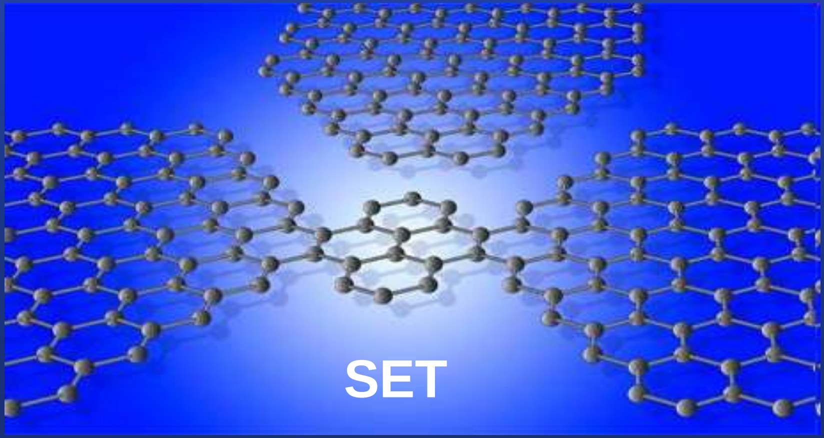




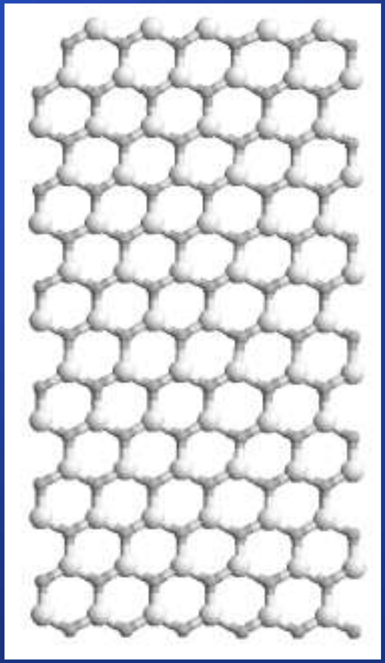
- Tiltott sáv létrehozása
- Él-hatások

Graphene quantum dots

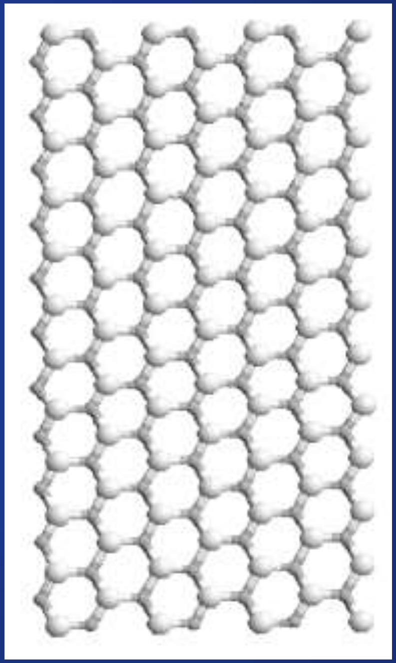




Graphene nanoribbons



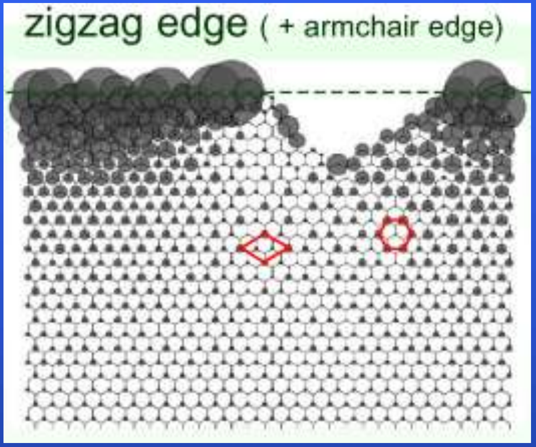
armchair

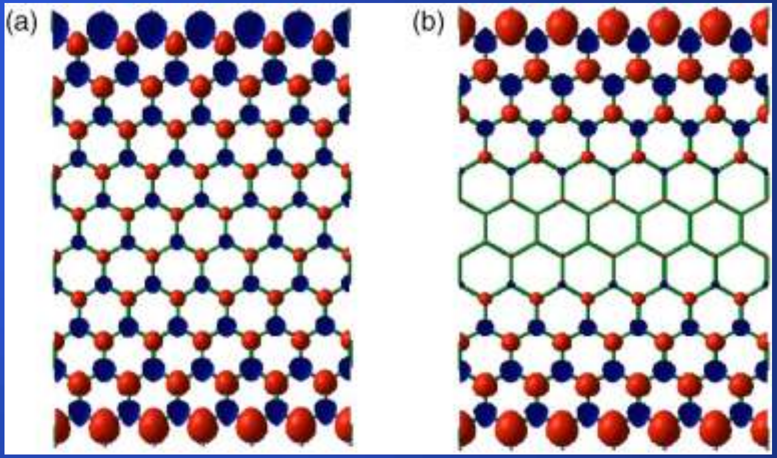


zigzag

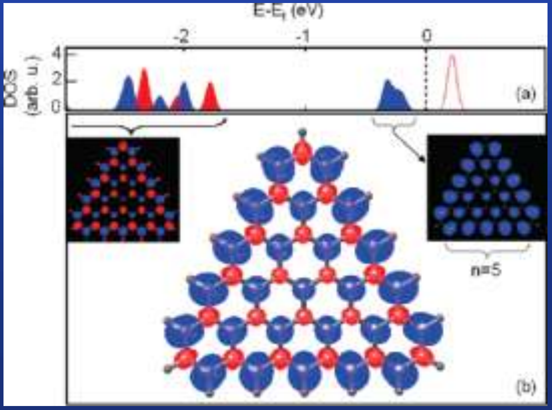
A grafén éleinek fizikája

L. Pisani, Phys. Rev. B 75, 064418 (2007)

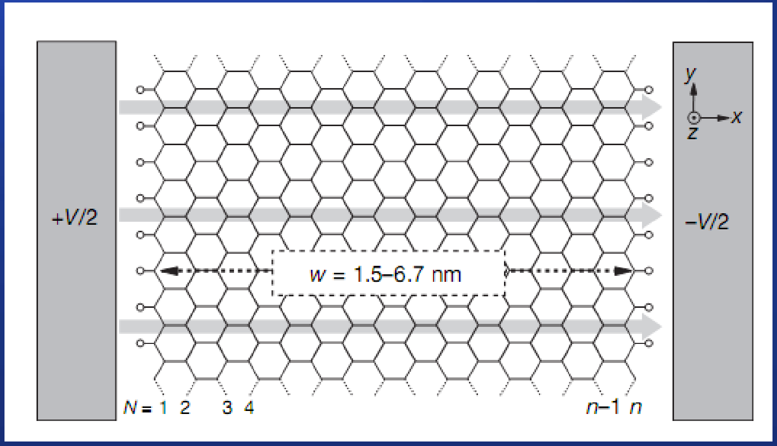




W.L Wang, Nano Lett. 8, 241 (2008)

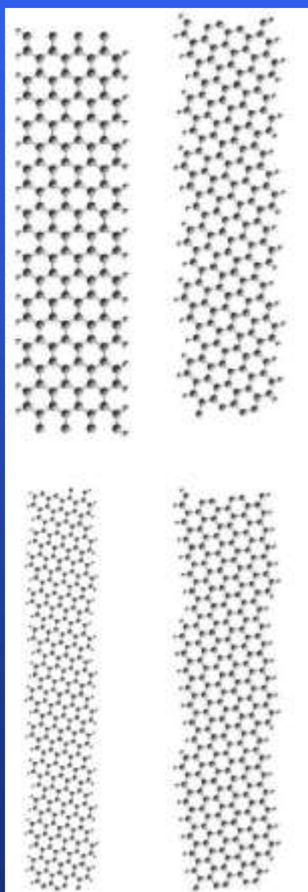


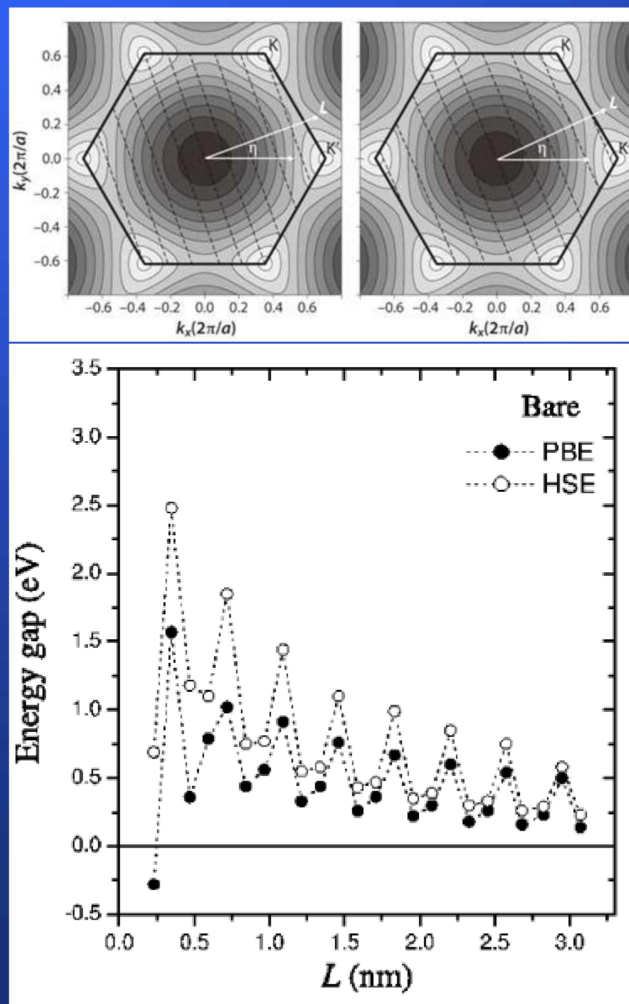
Y.V. Son Nature 444, 347 (2006)

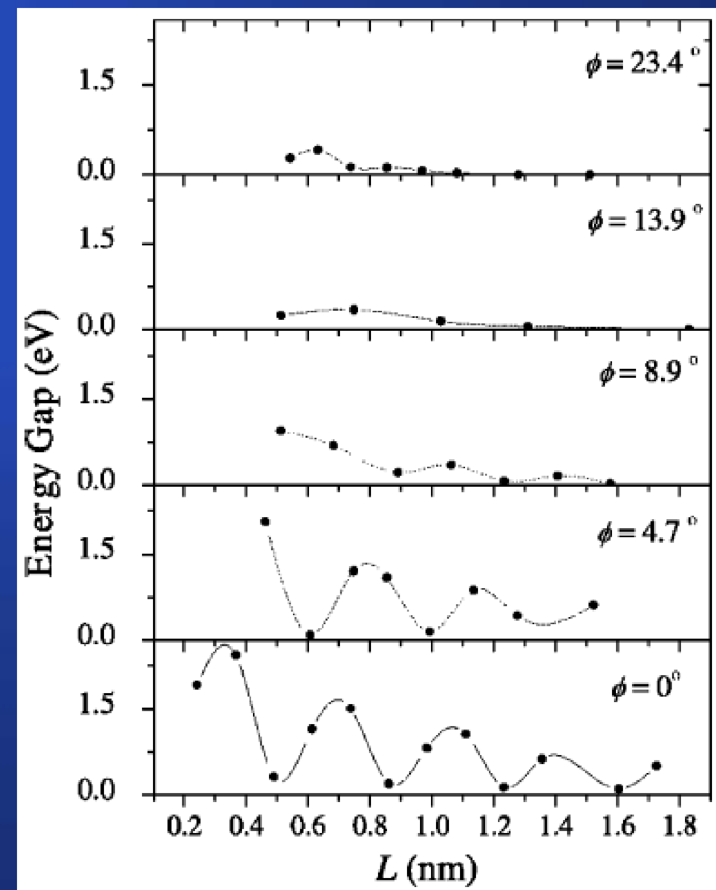


Grafén nanoszalagok – tiltott sáv

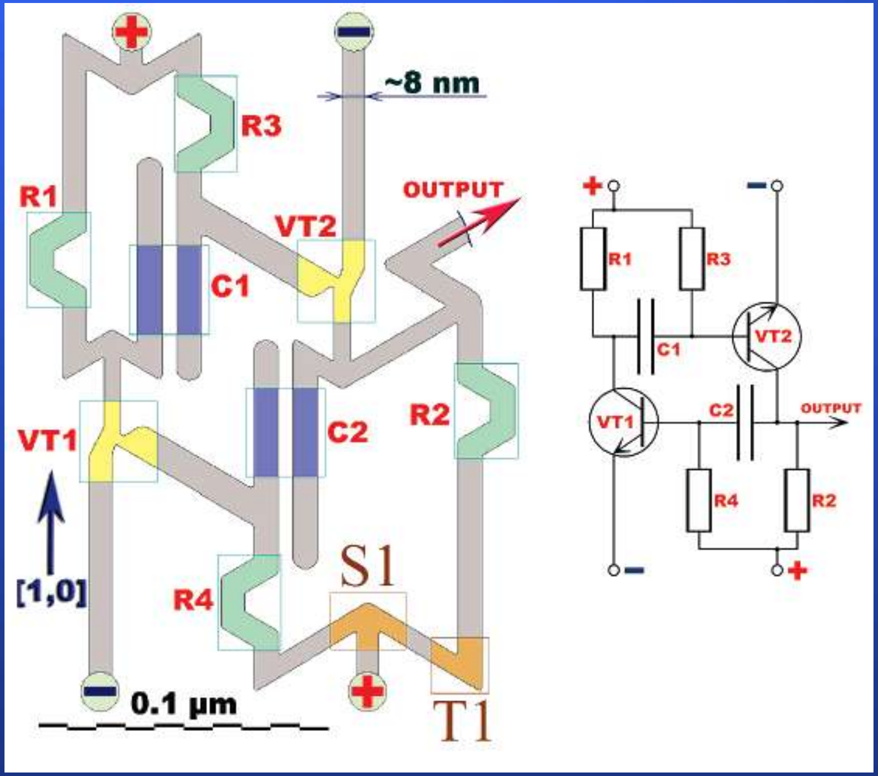
Nano Lett. 6, 2748 (2006)







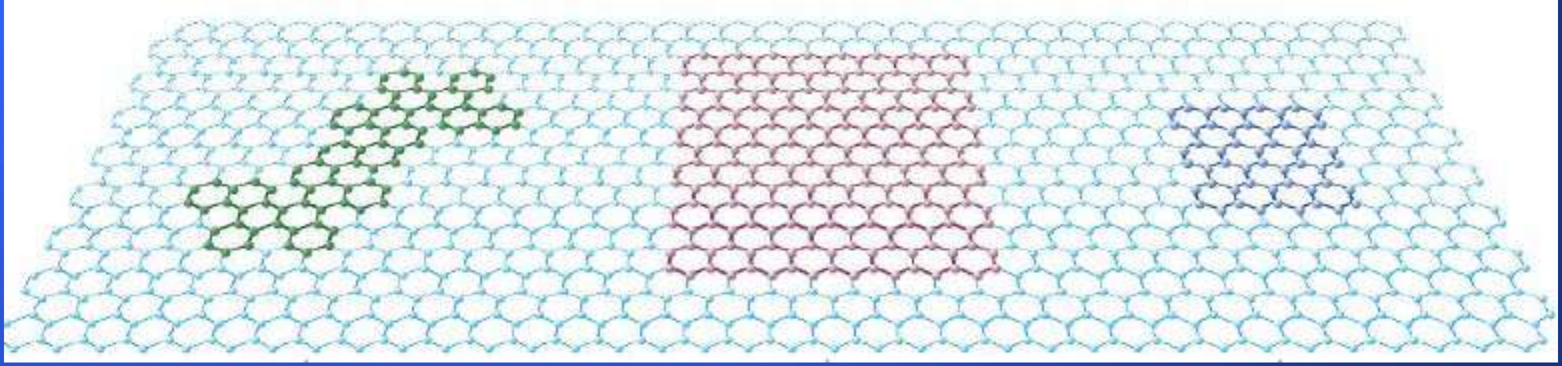
Grafén elektronika

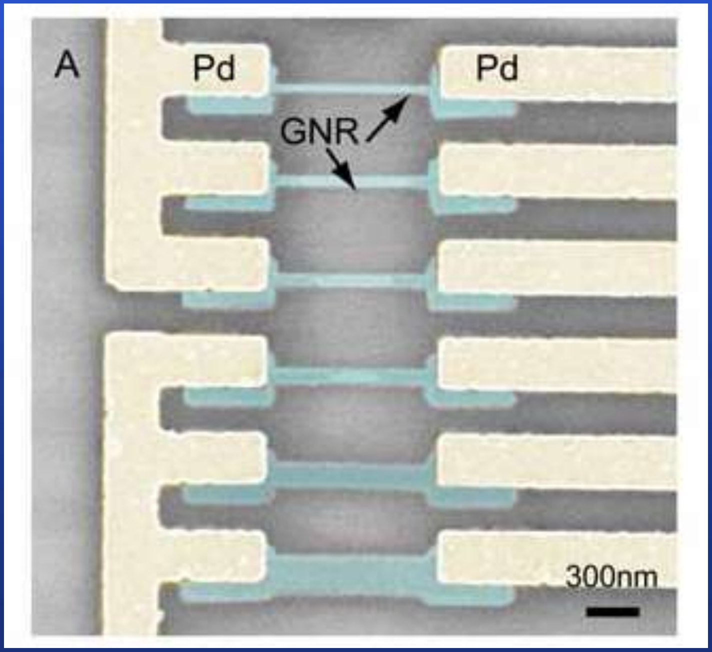


- Miniatürizálás – magasabb fokú integrálhatóság
- Gyorsabb eszközök
- Kisebb fogyasztás
- Nagyobb adatfeldolgozási kapacitás

D.A. Areshkin, Nano Lett. 7, 3253 (2007)

Grafén nanoszerkezetek előállítása



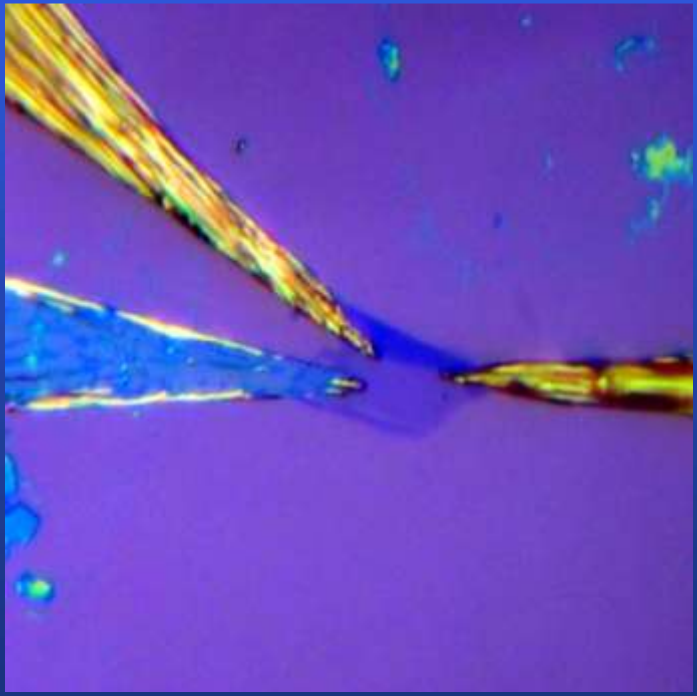


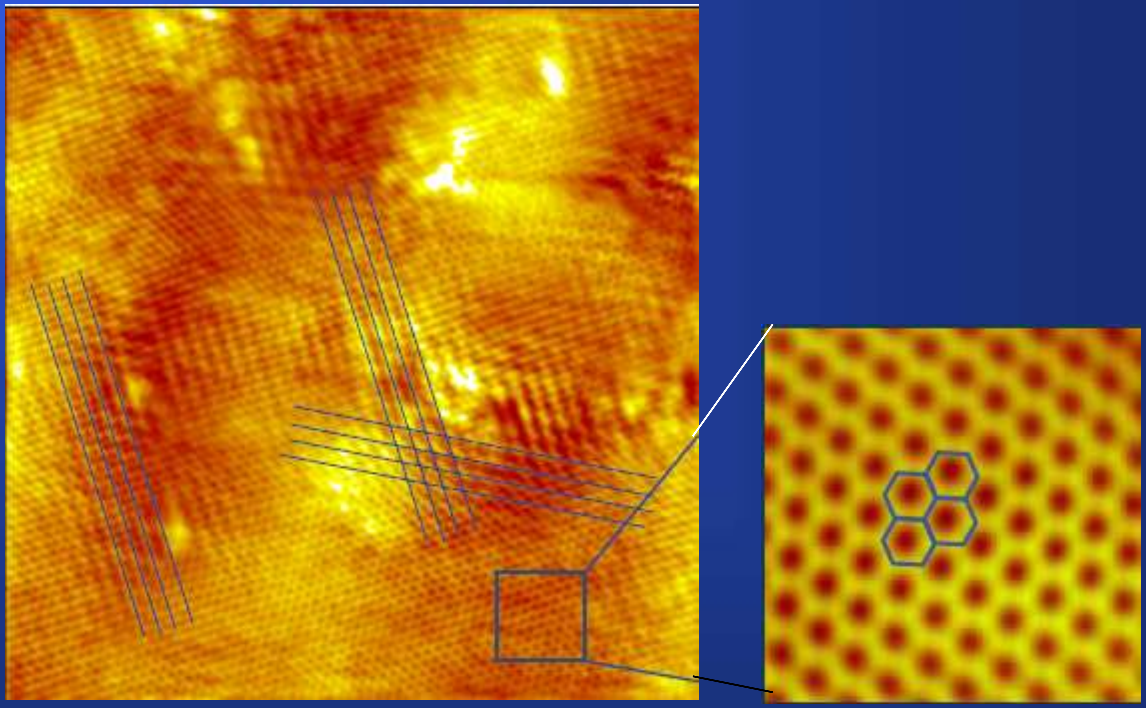
PRL 90, 206805 (2007)

Elektronsugaras litográfia

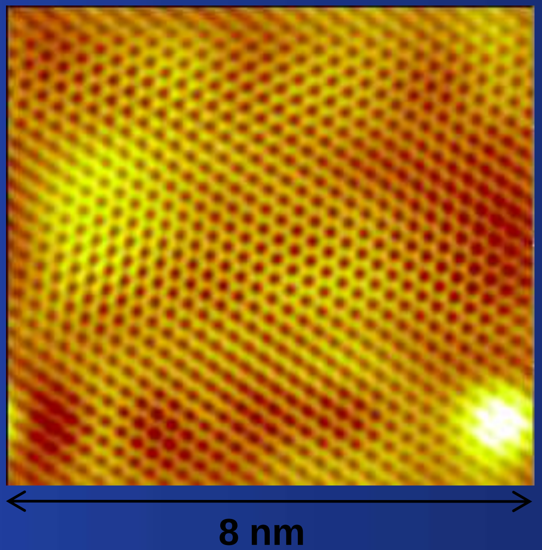
- a szalagok éleinek típusa nem kontrollálható
- minimális szalagszélesség > 15 nm
- „rojtos" szélek

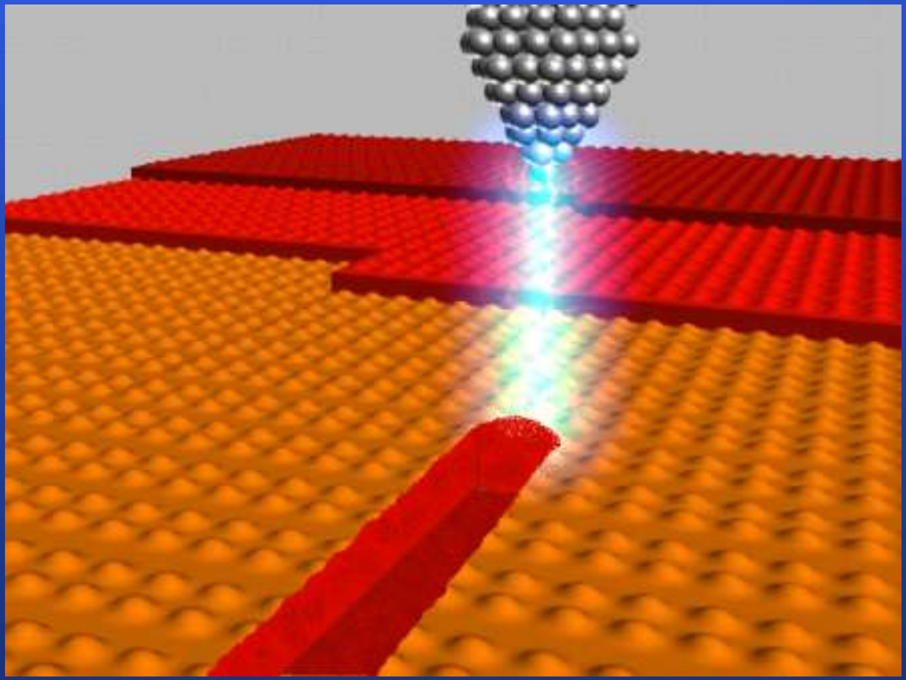
Grafén STM leképezése





STM Litográfia

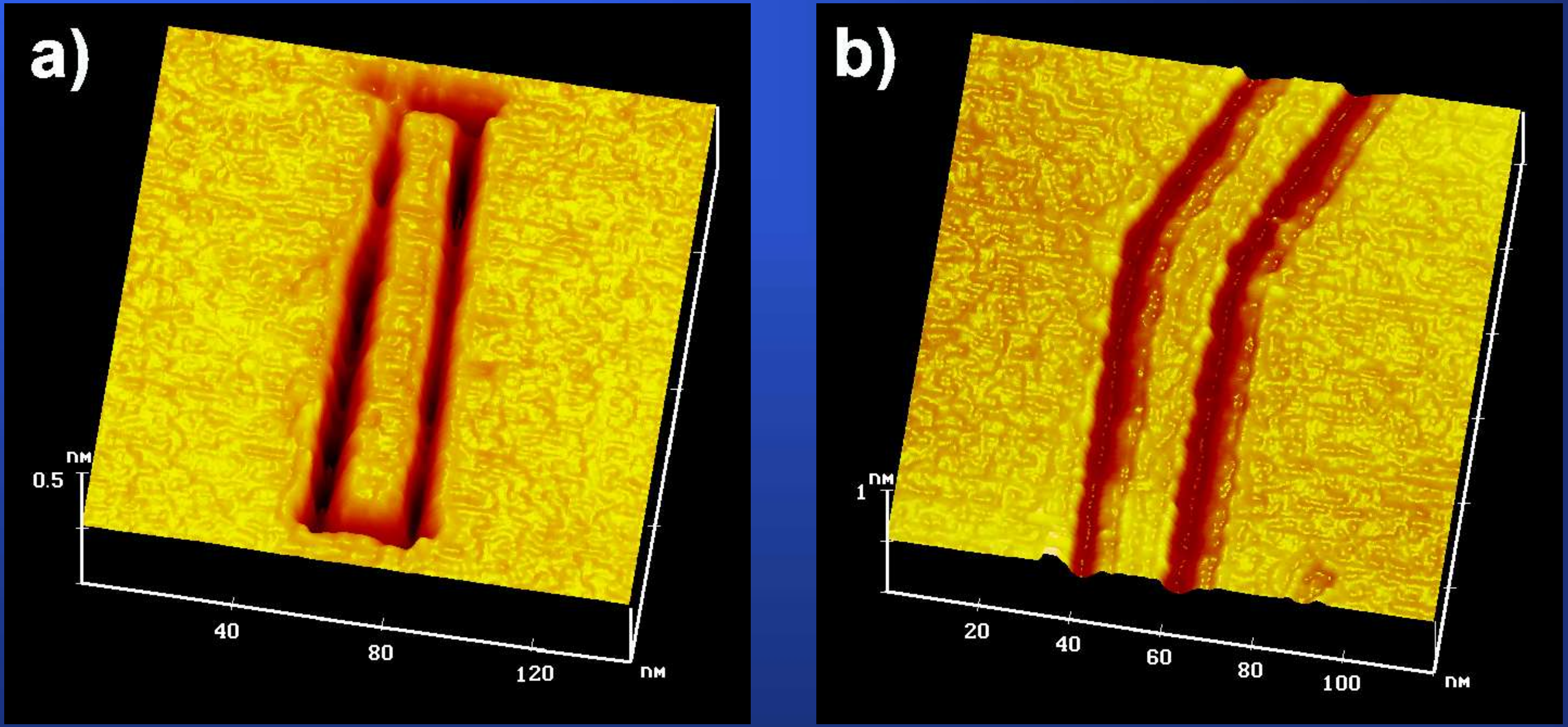




- Lokális módosítás – vágás
- Atomi felbontás
- Az élek orientációjának beállítása
- Atomi szinten pontos mozgatás
- Nanométeres pontosság

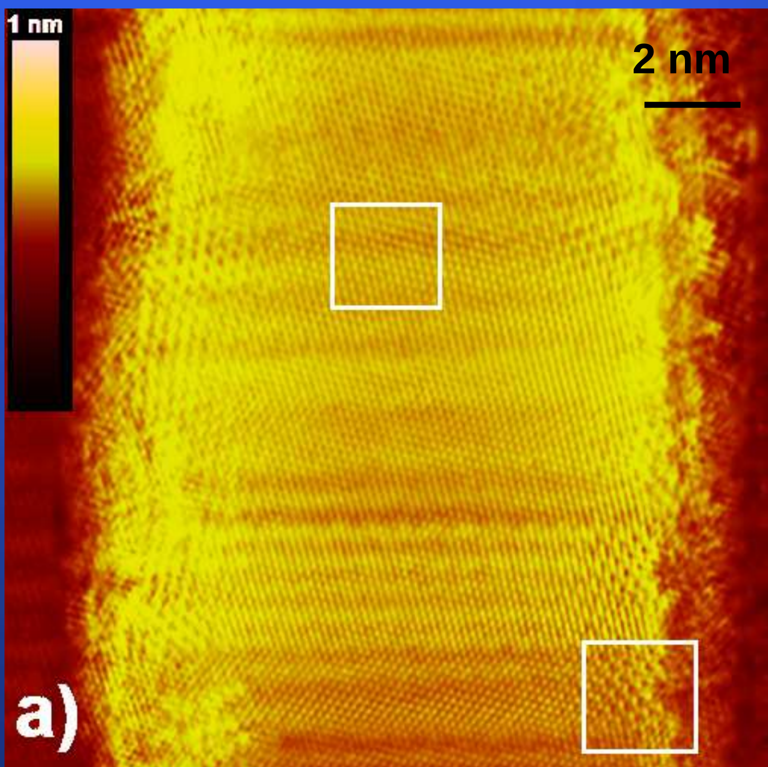
$C + H_2O \rightarrow CO + H_2 + 2e^-$

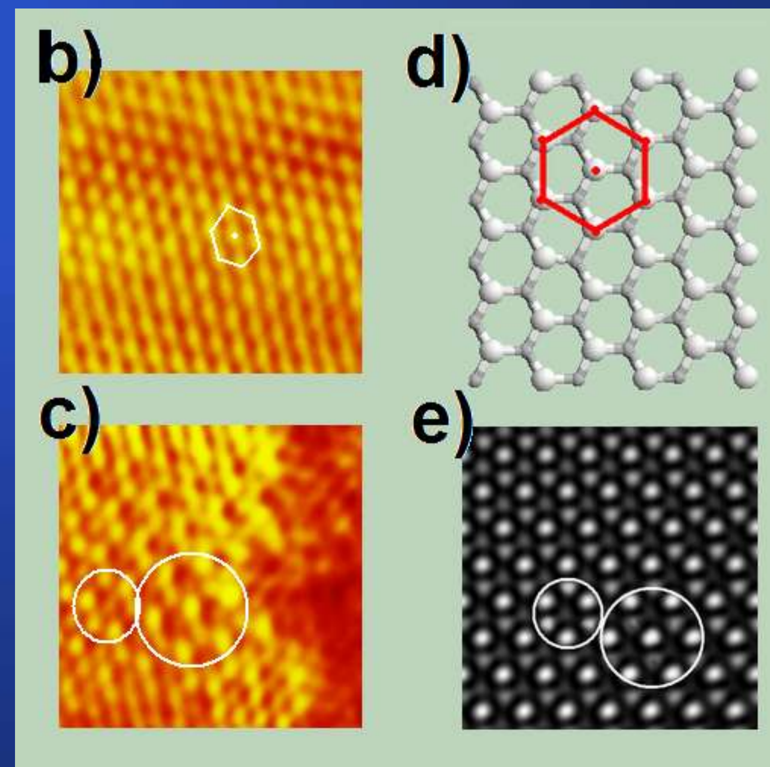
Grafén nanoszlagok létrehozása STM litográfiával



L.Tapasztó, Nature Nanotech. 3, 397 (2008)

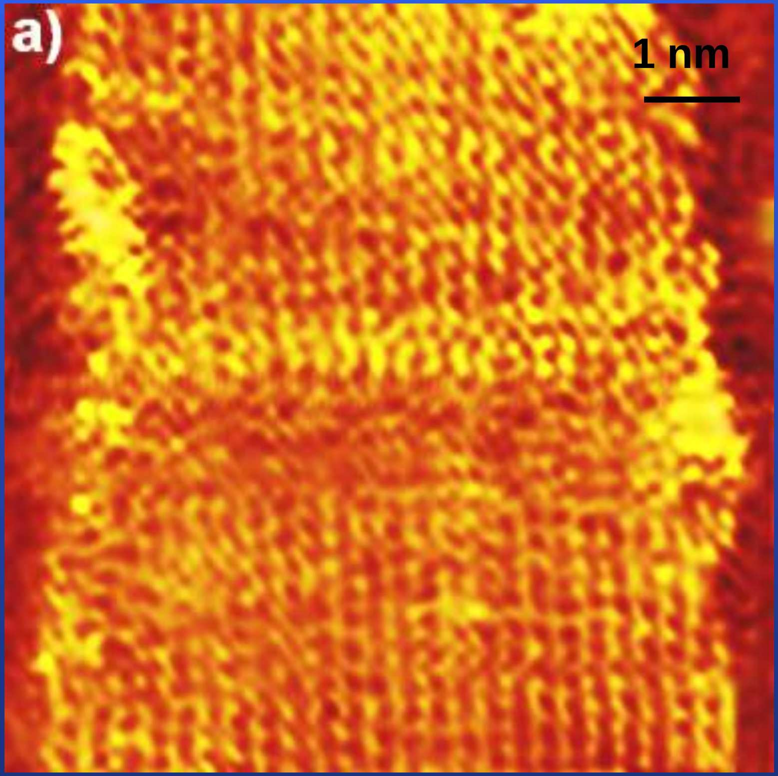
Grafén nanoszalagok szerkezte

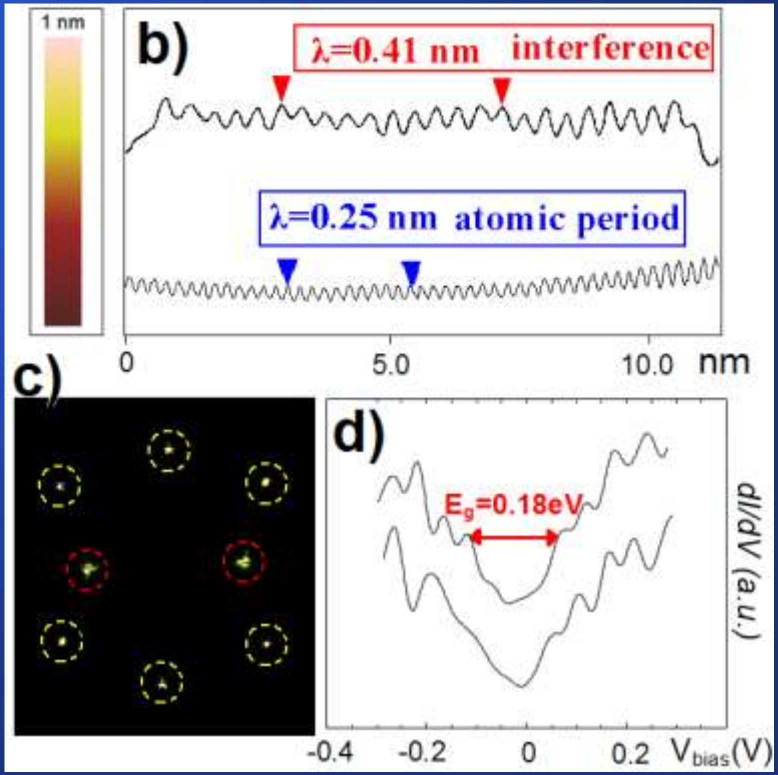




L.Tapasztó, Nature Nanotech. 3, 397 (2008)

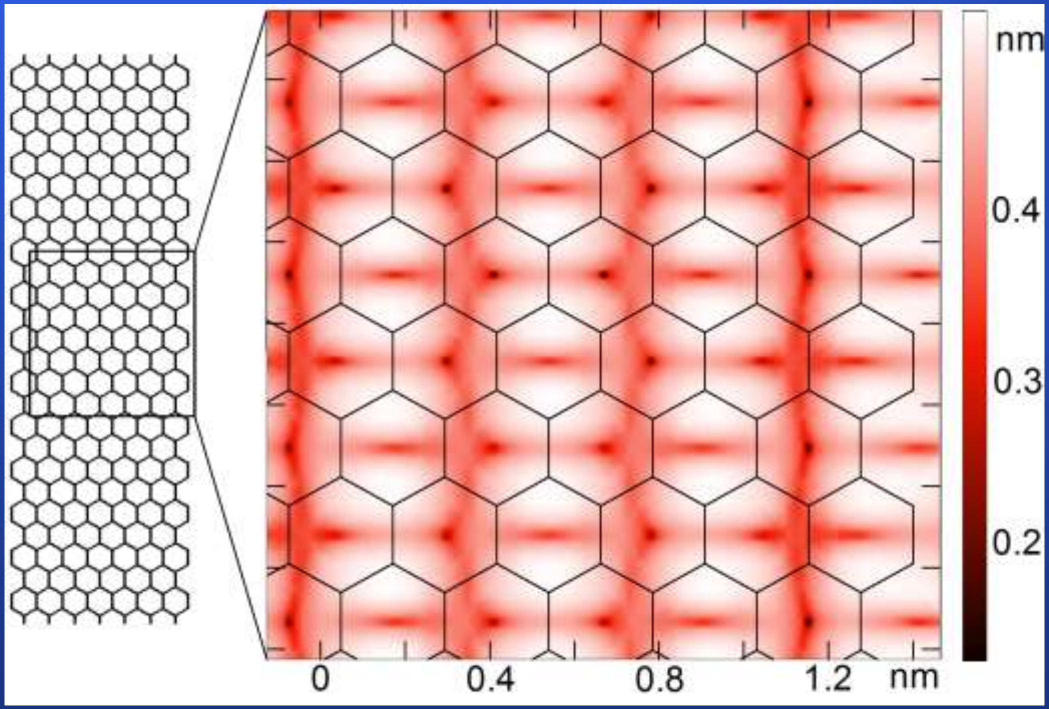
Elektron állóhullám grafénban

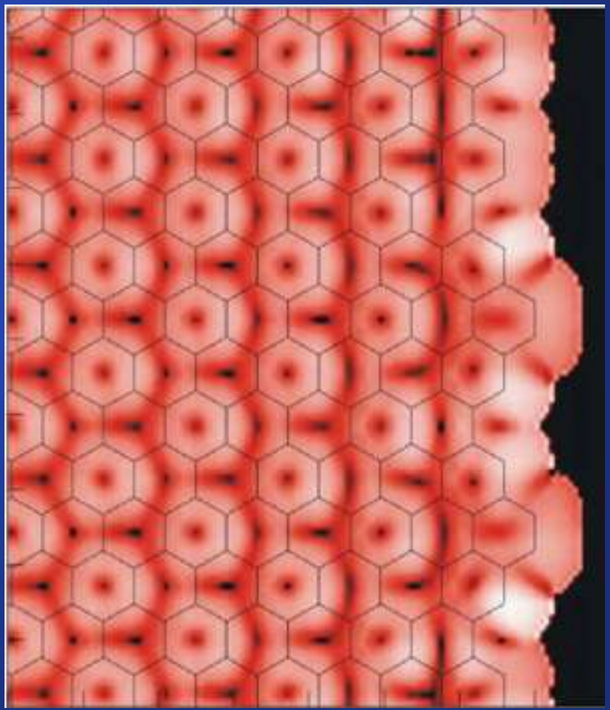




L.Tapasztó, Nature Nanotech. 3, 397 (2008)

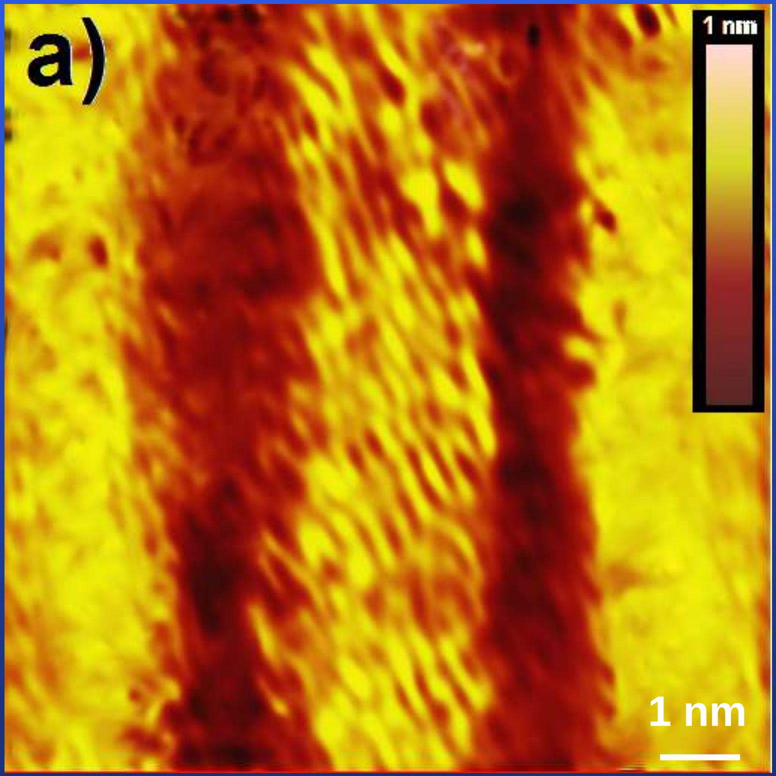
Elméleti STM képek

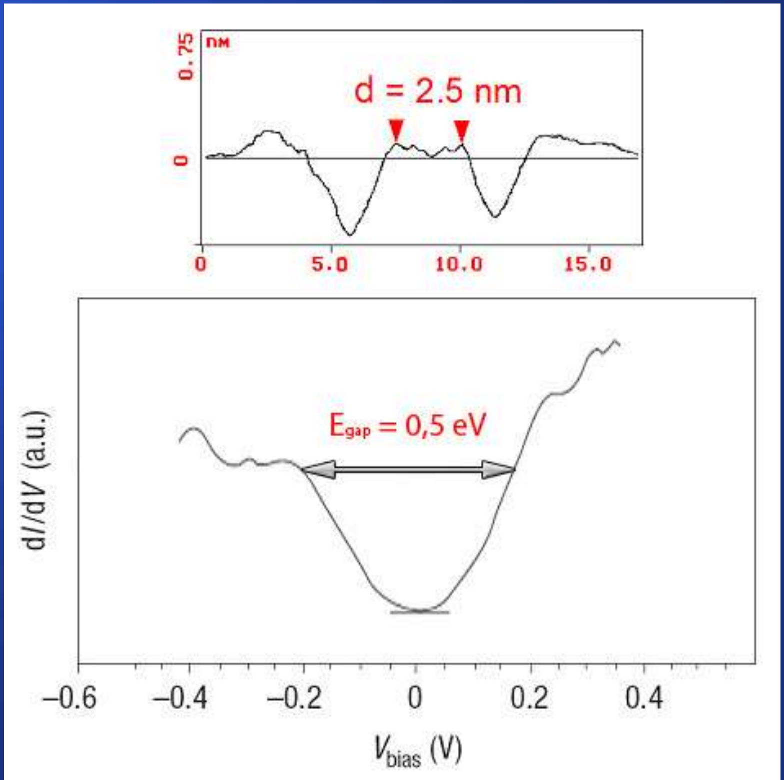




L.Tapasztó, Nature Nanotech. 3, 397 (2008)

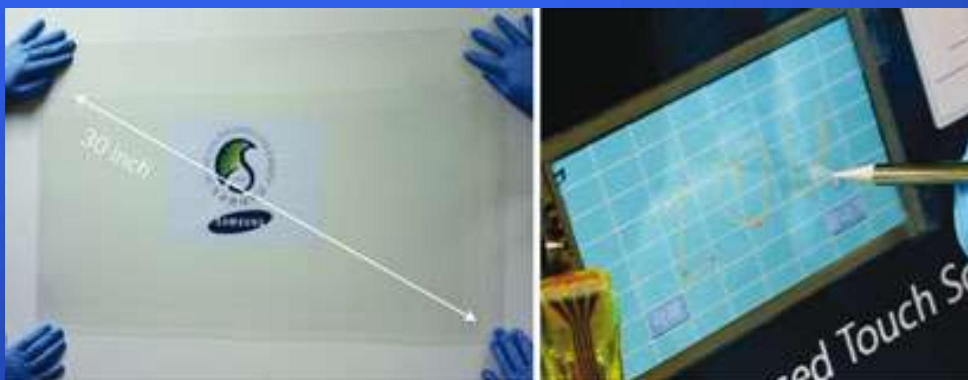
A létező legpontosabb nanomegmunkálási módszer





L.Tapasztó, Nature Nanotech. 3, 397 (2008)

Mit hoz a jövő?



közel

távol