What is Nanophysics: Survey of Course Topics

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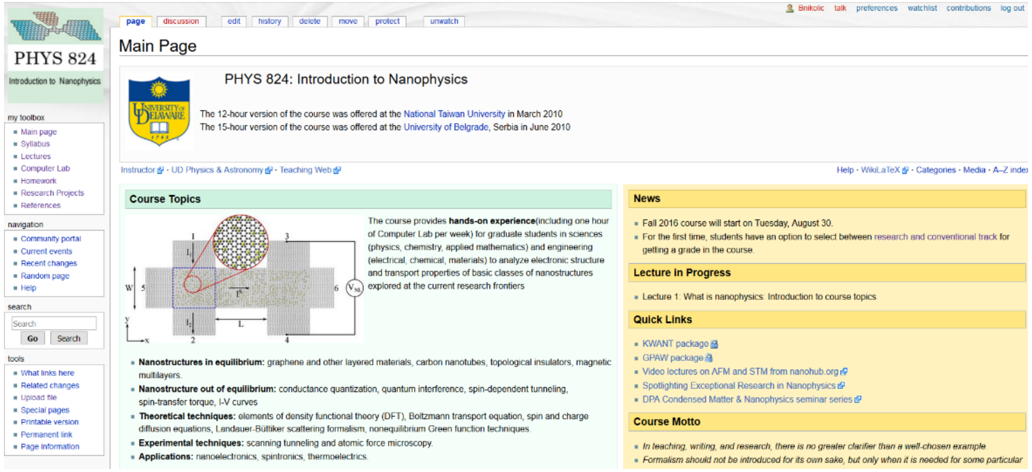
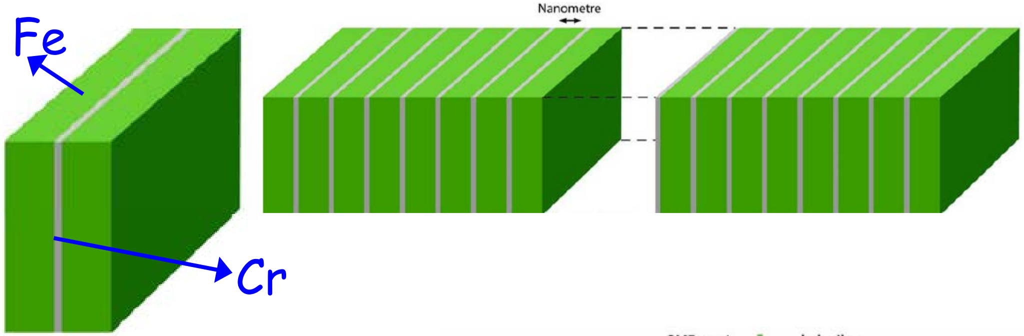
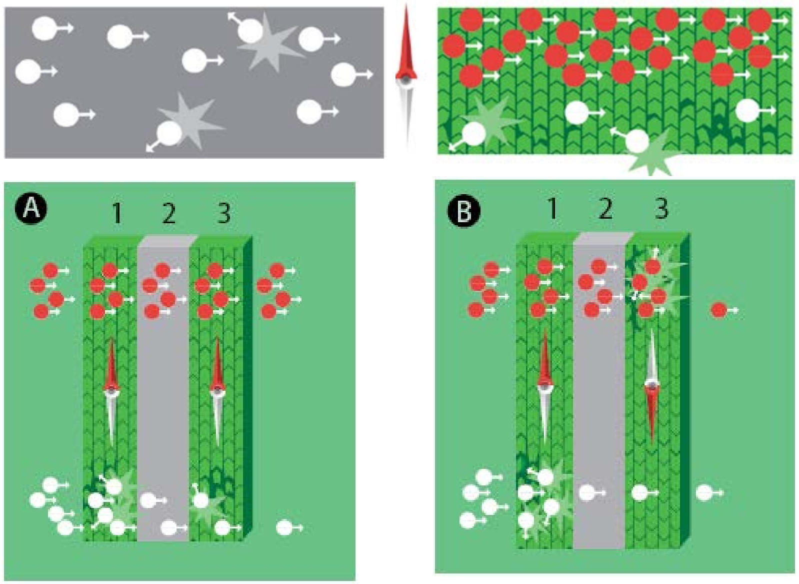
https://wiki.physics.udel.edu/qttg



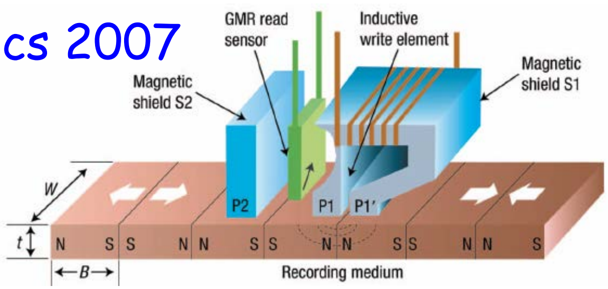
Definition of Nanophysical Systems

Definition: Any condensed matter systems whose at least one (out of three) dimension is of the order of **nanometer** can be considered as nanoscale system



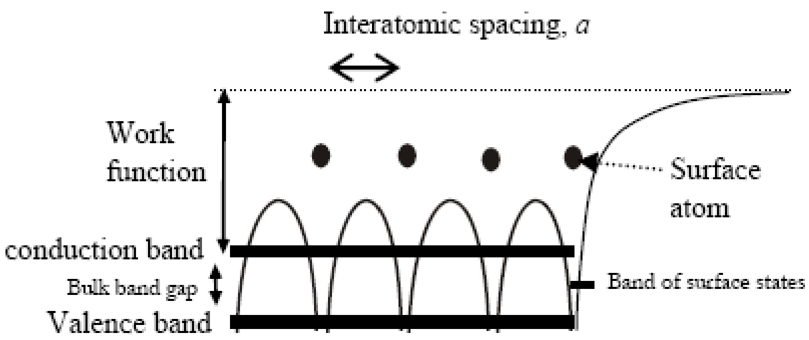


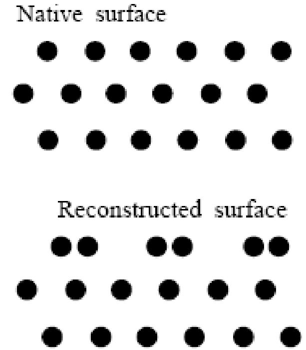
Nobel Prize in Physics 2007

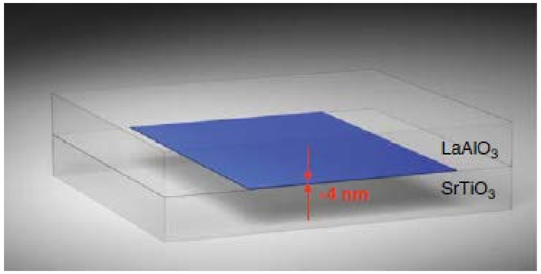


Nanoscience and nanotechnology are all about relating and exploiting phenomena for materials having one, two or three dimensions reduced to the nanoscale. Their evolution may be traced to three exciting happenings that took place in a short span from the early to mid-1980s with the award of Nobel prizes to each of them. These were: (i) the discovery quantum Hall effect in a two-dimensional electron gas; (ii) the invention of scanning tunnelling microscopy (STM); and (iii) the discovery of fullerene as the new form of carbon. The latter two, within a few years, further led to the remarkable invention of the atomic force microscope (AFM) and, in the early 1990s the extraordinary discovery of carbon nanotubes (CNT), which soon provided the launch pad for the present-day nanotechnology. The STM and AFM have emerged as the most powerful tools to examine, control and manipulate matter at the atomic, molecular and macromolecular scales and these functionalities constitute the mainstay of nanotechnology. Interestingly, this exciting possibility of nanolevel tailoring of materials was envisioned way back in 1959 by Richard Feynman in lecture entitled "There's plenty of room at the bottom."

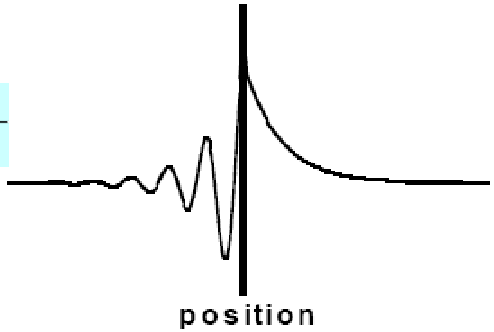
W. Pauli: "God made solids, but surfaces were the work of Devil."

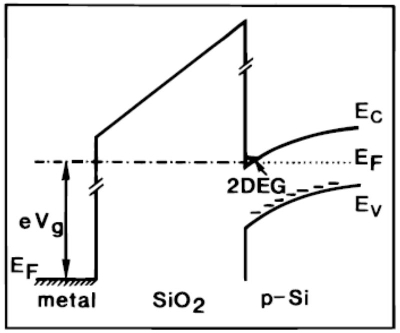


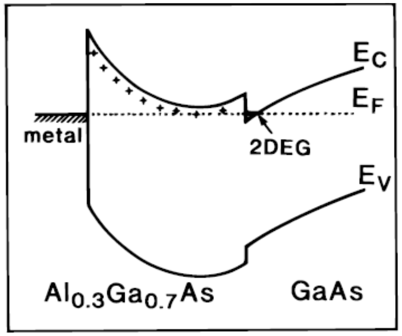


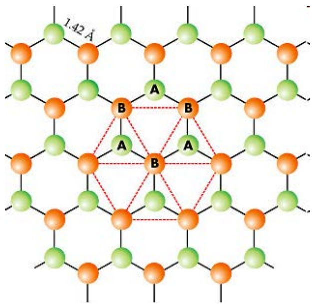


$$\Psi(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{\mathbf{k}}(\mathbf{r}) \rightarrow \Psi^{\mathrm{surf}}(\mathbf{r}) = e^{i\mathbf{k}_{||}\cdot\mathbf{r}_{||}} u_{\mathbf{k}_{||}}(\mathbf{r}_{||}) e^{-\mathbf{k}_{\perp}\cdot\mathbf{r}_{\perp}}$$

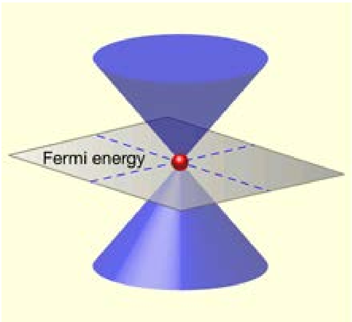


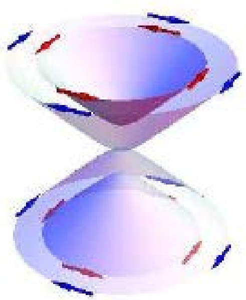




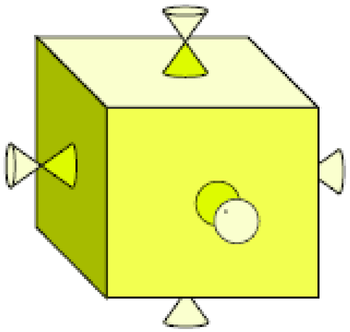


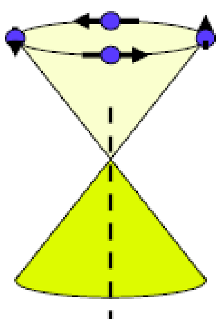
Graphene as pure surface



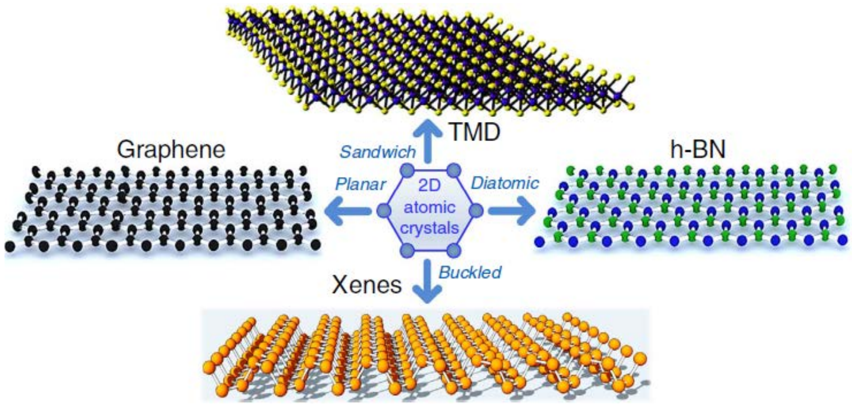


Metallic surfaces of 3D topological insulators

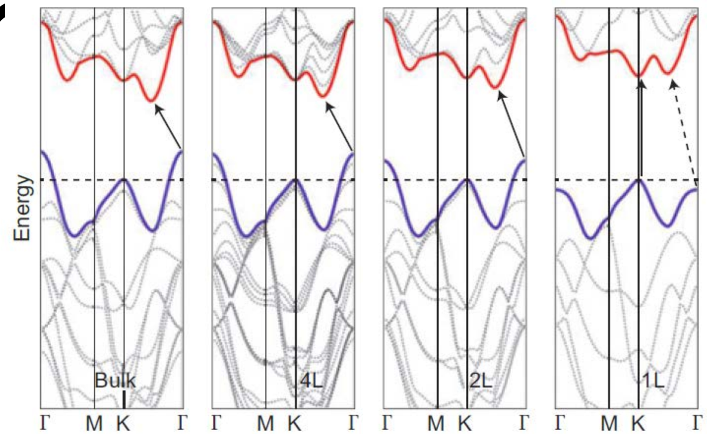


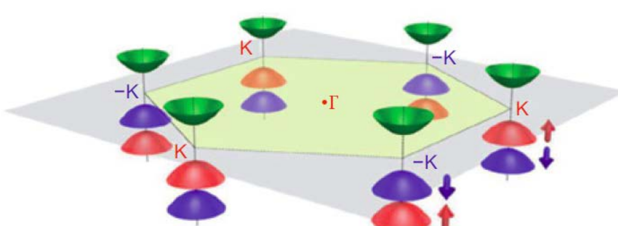


Two-Dimensional Materials Beyond Graphene and their van der Waals Heterostructures



MoS_2





REVIEW

APPLIED PHYSICS

2D materials and van der Waals heterostructures

K. S. Novoselov,[1,2]* A. Mishchenko,[1,2] A. Carvalho,[3] A. H. Castro Neto[3]*

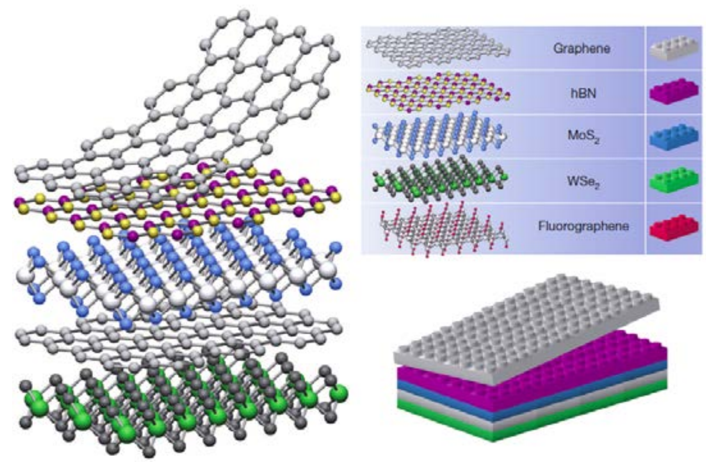
PERSPECTIVE

doi:10.1038/nature12385

Van der Waals heterostructures

A. K. Geim[1,2] & I. V. Grigorieva[1]

van der Waals heterostructure is a type of metamaterial that consists of vertically stacked two-dimensional materials as building blocks held together by the van der Waals forces between the layers

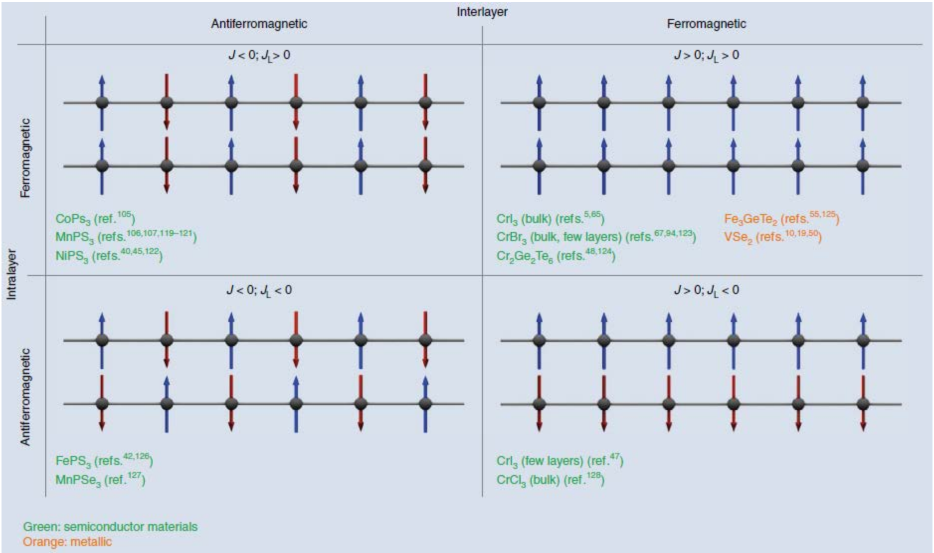


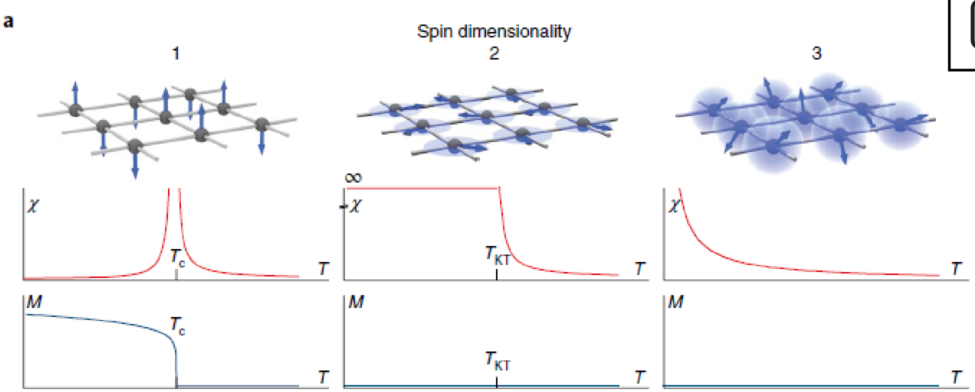
Two-Dimensional Magnetic Materials

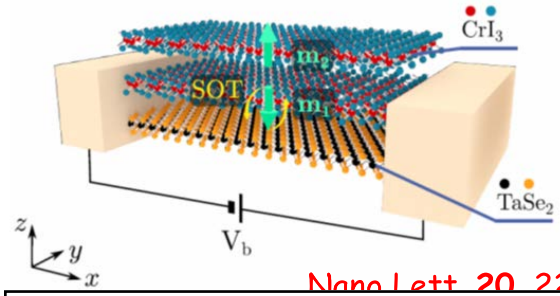
REVIEW ARTICLE | nature nanotechnology
https://doi.org/10.1038/s41565-019-0438-6

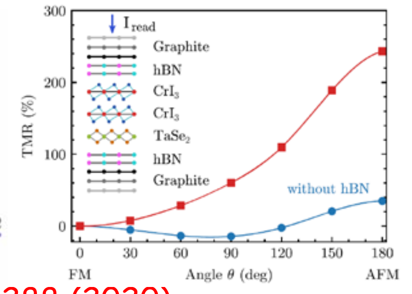
Magnetic 2D materials and heterostructures

M. Gibertini[1,2], M. Koperski[3,4], A. F. Morpurgo[1,5] and K. S. Novoselov[3,4]*

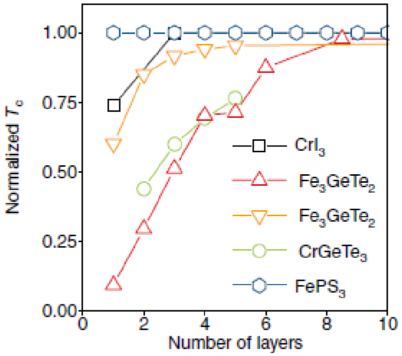


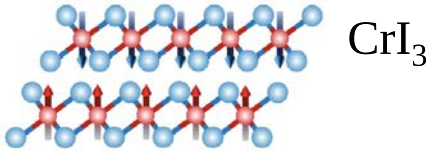


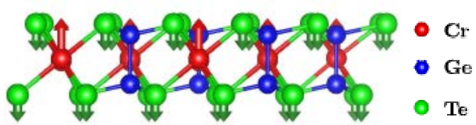




Nano Lett. 20, 2288 (2020)

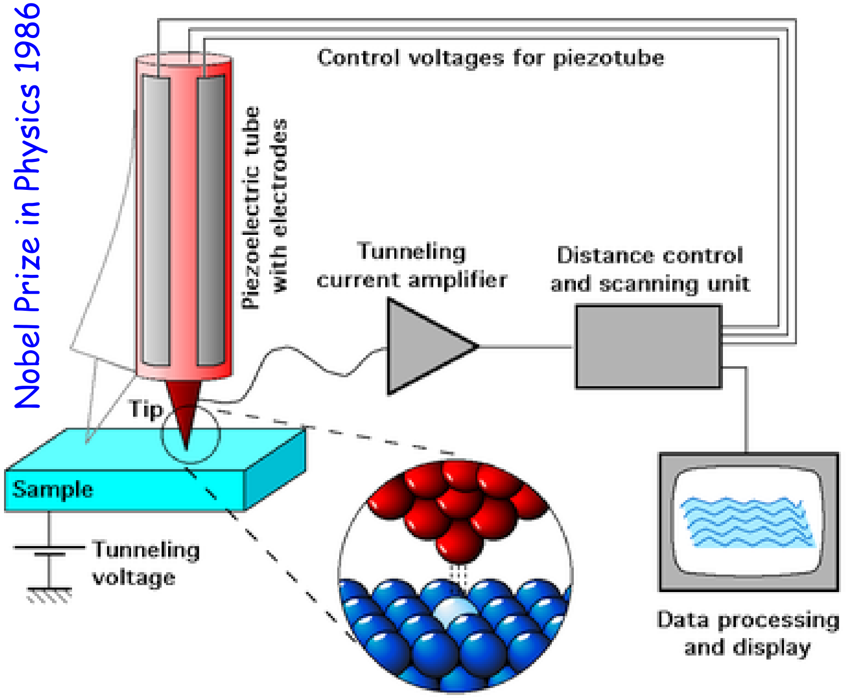


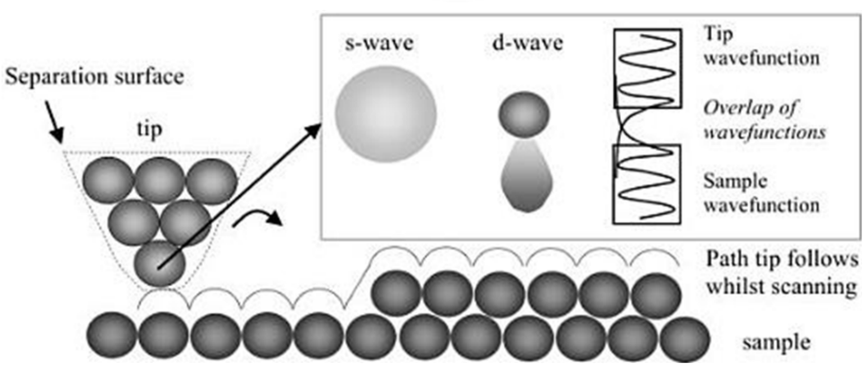


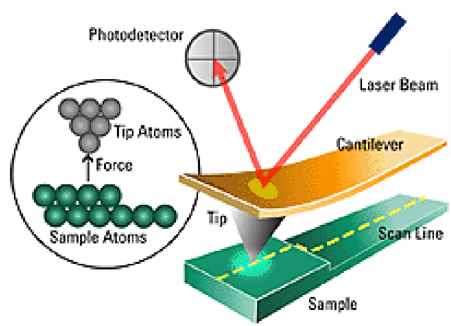


Experimental Tools of Nanophysics: STM and AFM

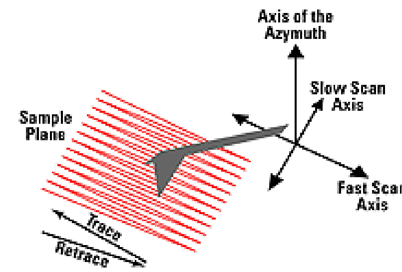
Nobel Prize in Physics 1986





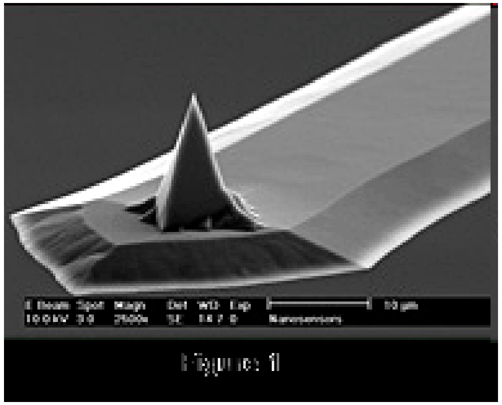


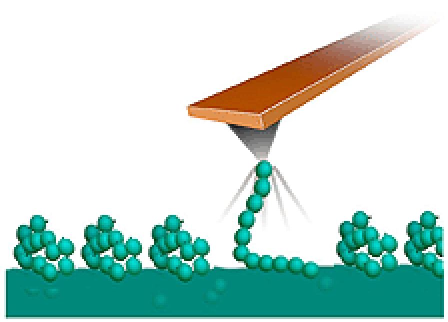
(Figure 4)



(Figure 4a)

The main function of the feedback system is to move the sample and the tip relative to each other. The movement in the plane of the sample is called raster-scanning, and is well-defined once the user sets the scan area and scan speed (Figure 4a). The movement out of the plane of the sample is completely unpredictable, and it is this movement that underlies the construction of three dimensional topography images. The height of features in an AFM image is determined by how far up and down the tip or sample move relative to each other in order to maintain a constant tip-sample interaction force. In some AFM's the tip moves up-down while the sample stays at a constant height; in other AFM's this scheme is reversed. The end result is, in principle, the same.

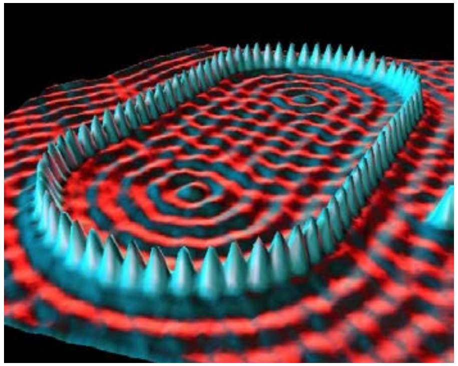


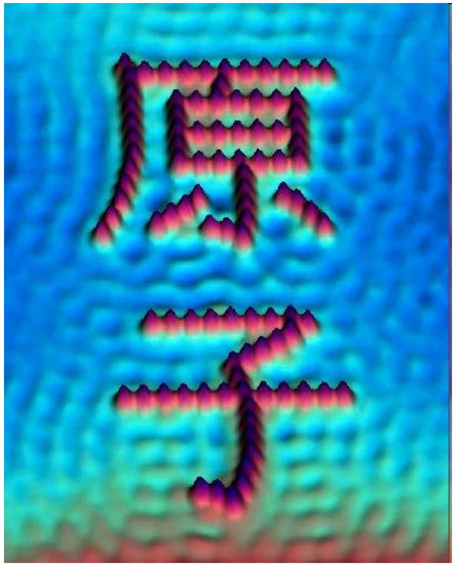


(Figure 9) Force Pulling illustration

Examples of STM Images

Fe on Cu(111)



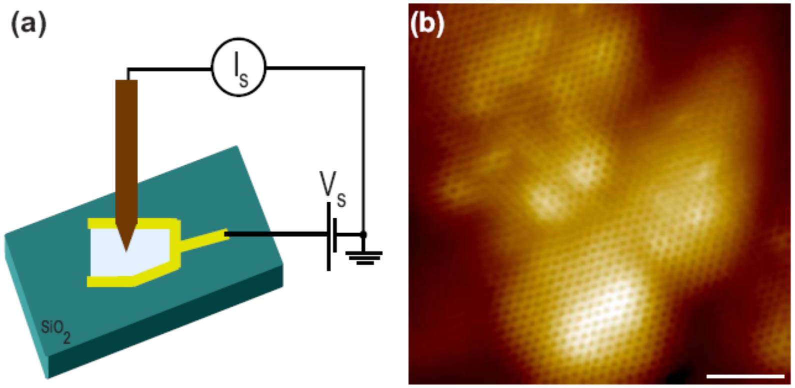


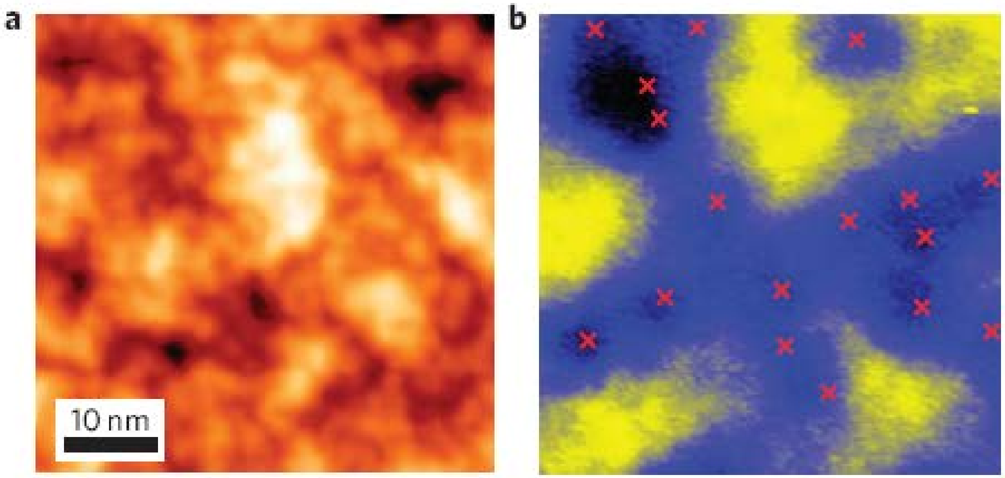
IBM Almaden

LETTERS
nature physics
PUBLISHED ONLINE: 30 AUGUST 2009 | DOI: 10.1038/NPHYS1365

Origin of spatial charge inhomogeneity in graphene

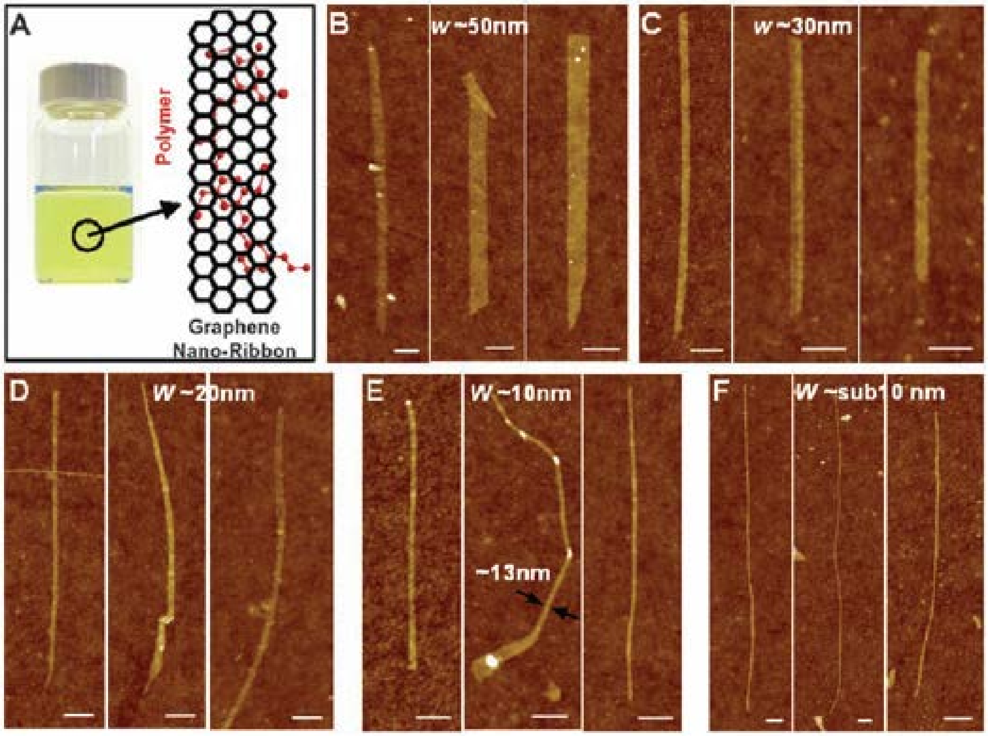
Yuanbo Zhang[1*†], Victor W. Brar[1,2*], Caglar Girit[1,2], Alex Zettl[1,2] and Michael F. Crommie[1,2†]



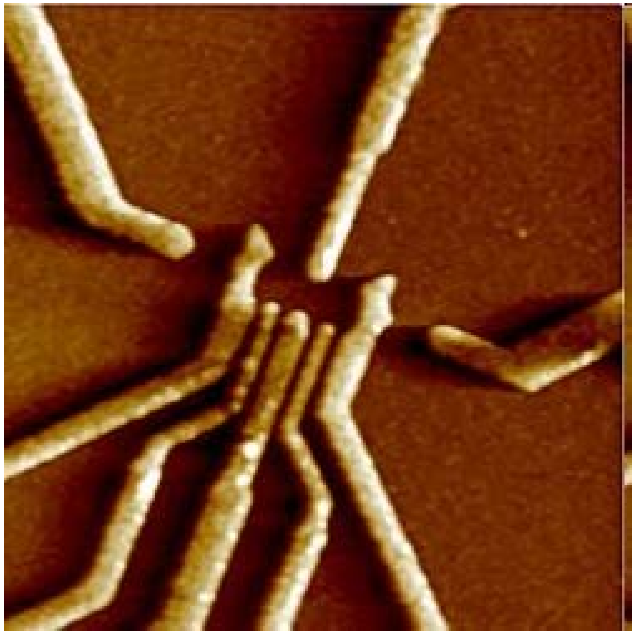


Examples of AFM Images

Science **319**, 1229 (2008):
Graphene Nanoribbons with ultrasmooth edges



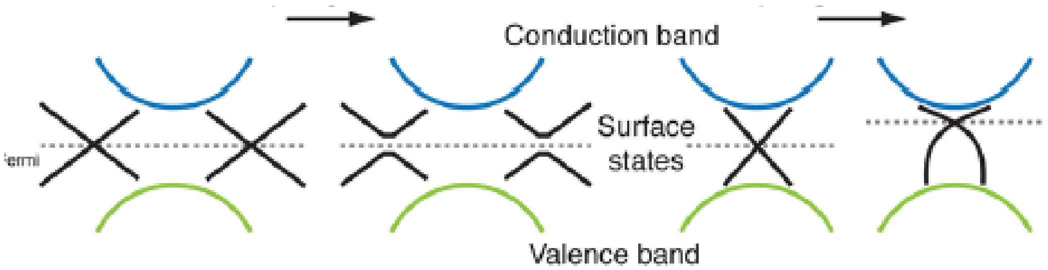
Kouwenhoven Lab:
Double quantum dot integrated with quantum point contacts on both sides as a spin-based qubit

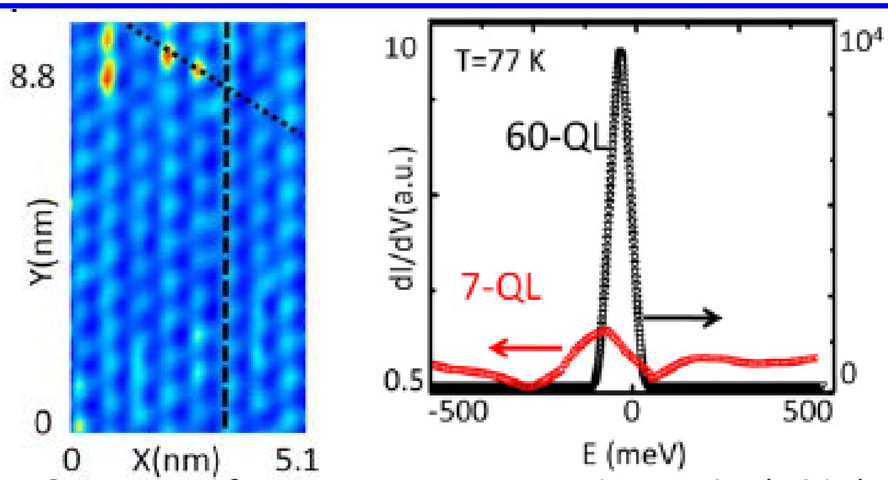


Physical Meaning of Dirac Materials and Topological Protection Revealed by STM

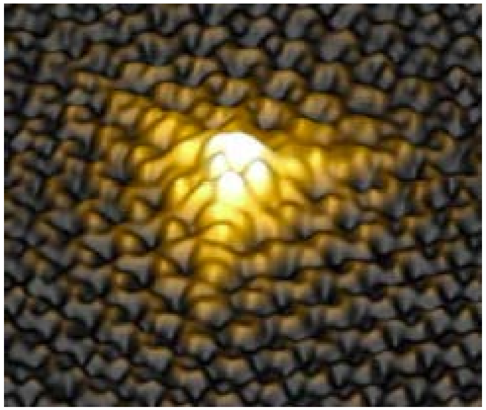
perturbing topologically trivial Dirac material such as graphene

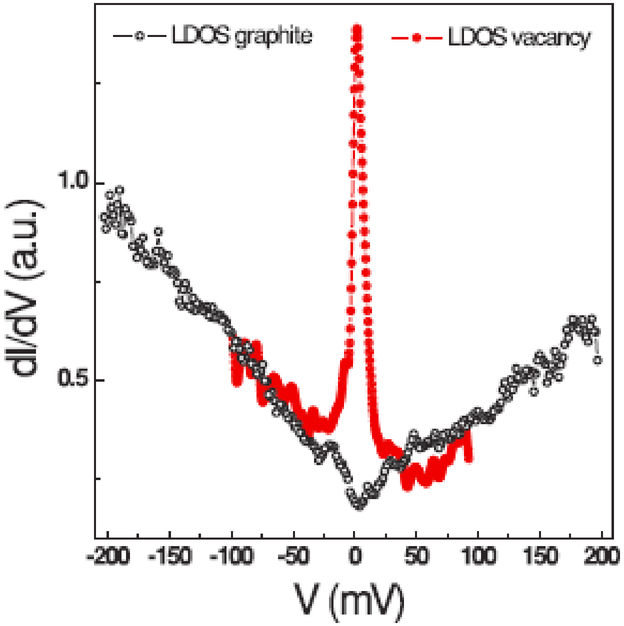
perturbing topological insulators as Dirac materials with nontrivial topology of wavefunctions in the bulk





Bi_2Se_3 surface + impurity: SSC **152**, 747 (2012)

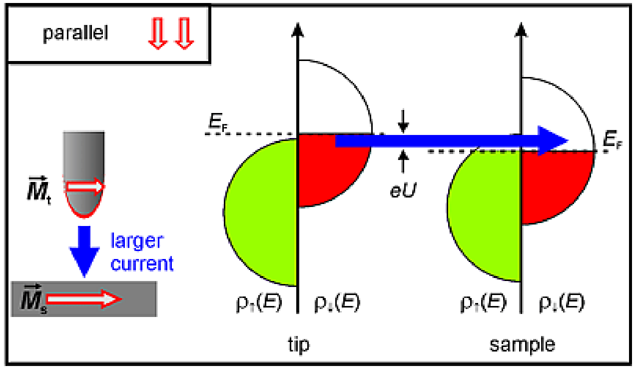


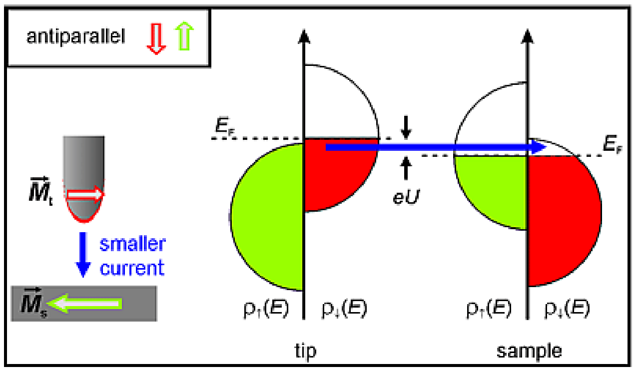


graphene + vacancy: PRL **104**, 096804 (2010)

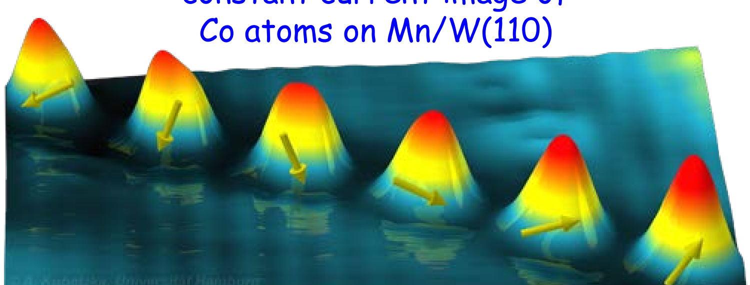
Nanoscale Imaging of 2D Magnets: SP-STM and MFM plus SQUID (SSM) and scanning NV center microscopy (SNVM)

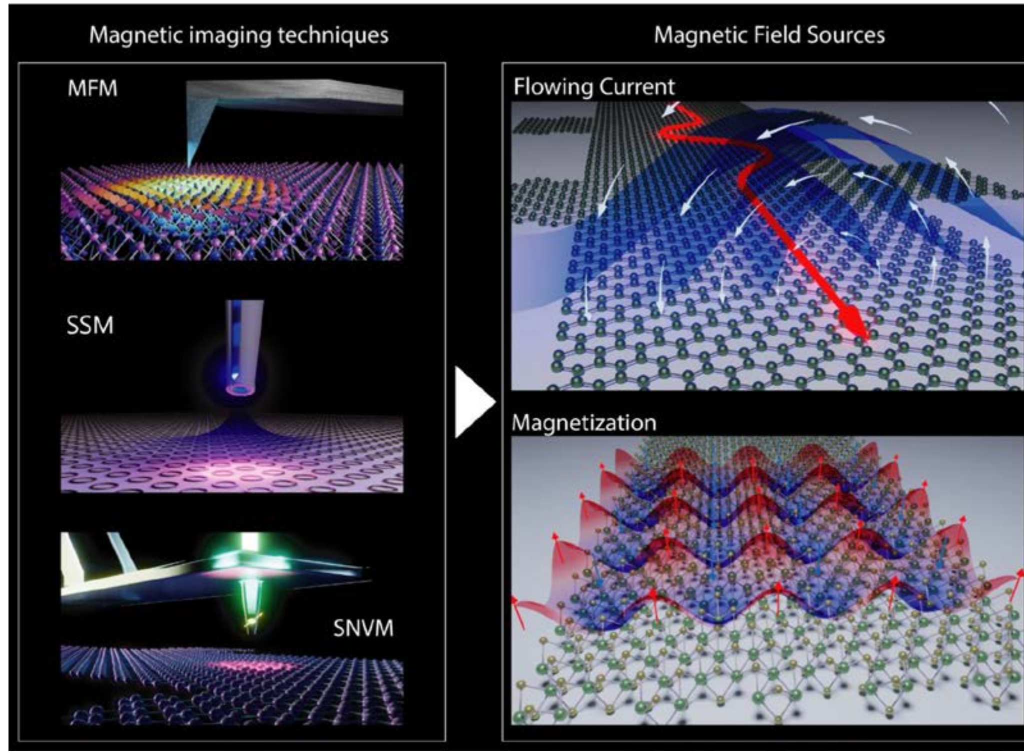
Nat. Nanotech. **10**, 350 (2010)





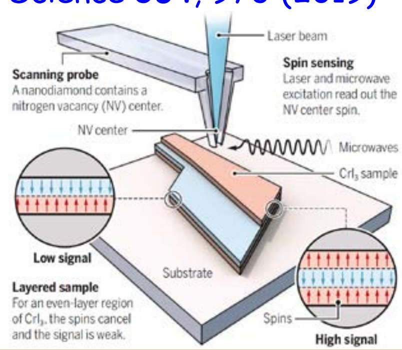
constant current image of Co atoms on Mn/W(110)

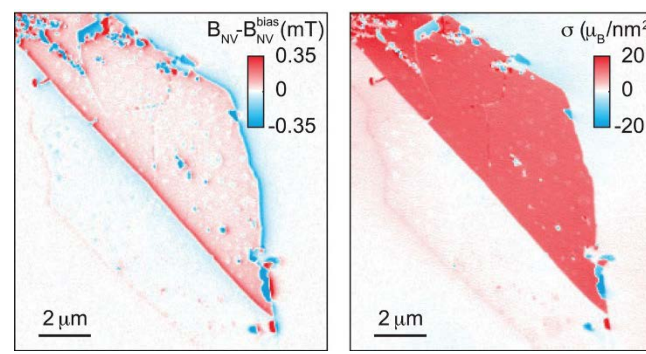




Nat. Rev. Phys. 4, 49 (2022)

Science **364**, 973 (2019)





Why are Nanostructures Interesting for Basic Research on Weakly Interacting Electrons?

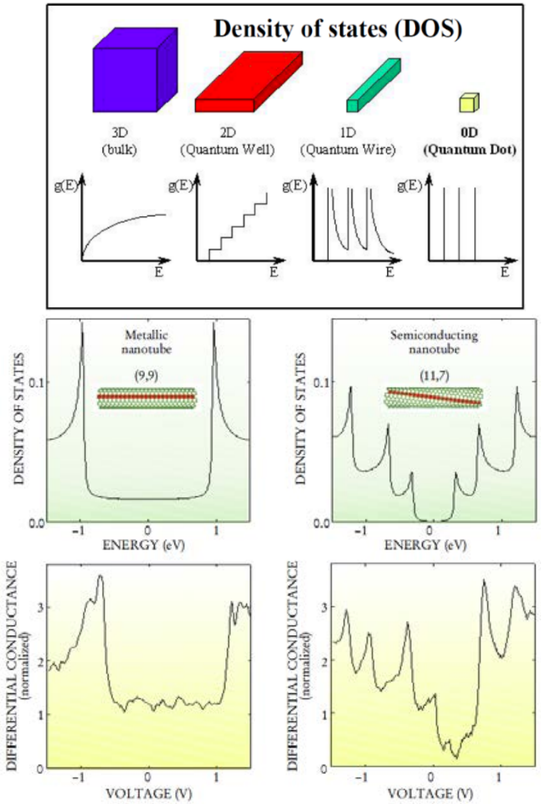
- Enhanced role of surface atoms with unpaired spins and uncompensated bonds
- Reduced dimensionality at the nanoscale = strongly modified density of states, enhanced Coulomb interaction, …

equilibrium branch of the course

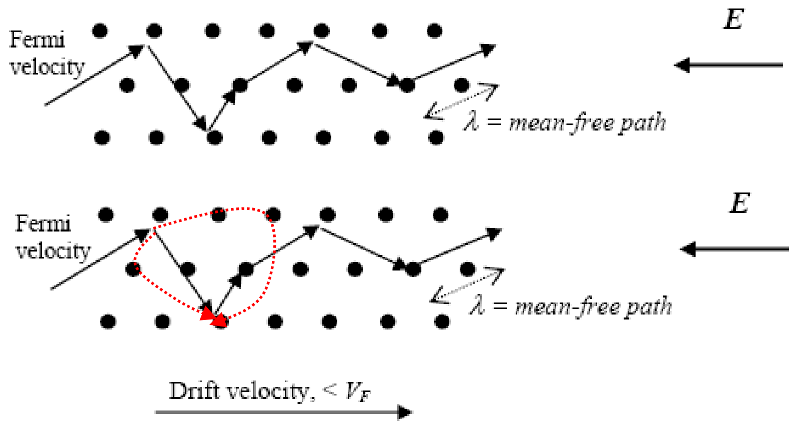
- Quantum confinement effects = discrete energy levels, and modified DOS subbands

nonequilibrium branch of the course

- Quantum interference effects in transport = quantum transport



Phys. Today, May 1999



$$P_{\rm cl} = P_1 + P_2 \text{ vs. } P_{\rm qm} = |A_1 + A_2|^2$$

$$P_{\rm qm} = P_1 + P_2 + 2\sqrt{P_1 P_2}\cos\phi$$

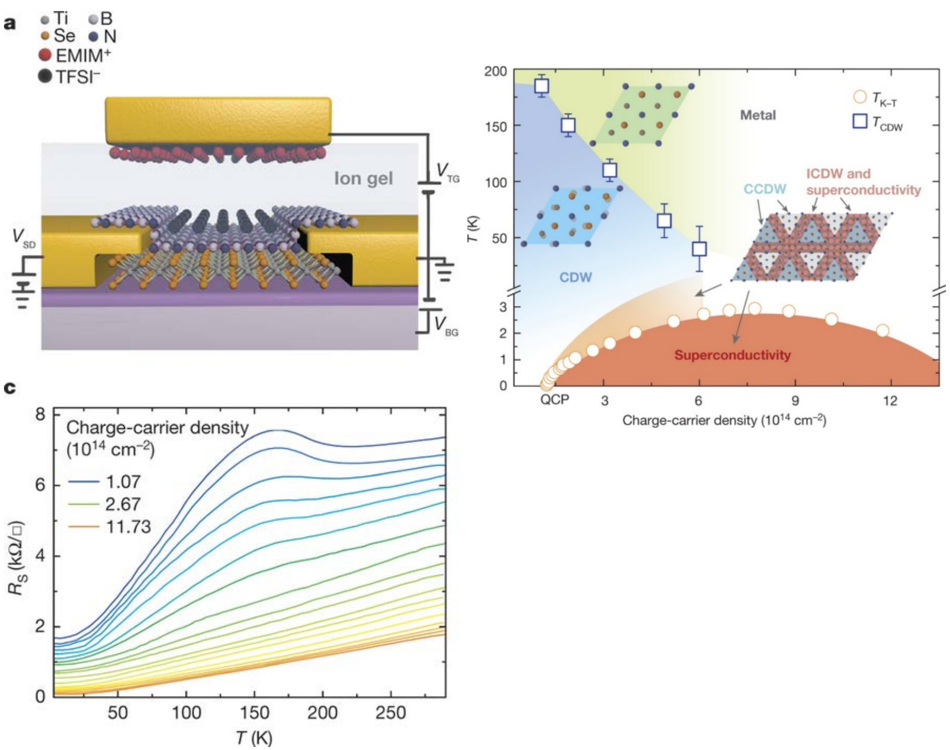
Why are Nanostructures Interesting for Basic Research on Strongly Interacting Electrons?

LETTER

doi:10.1038/nature16175

Controlling many-body states by the electric-field effect in a two-dimensional material

L. J. Li[1,2,3*], E. C. T. O'Farrell[1,2*], K. P. Loh[1,3], G. Eda[1,2,3], B. Özyilmaz[1,2] & A. H. Castro Neto[1,2]

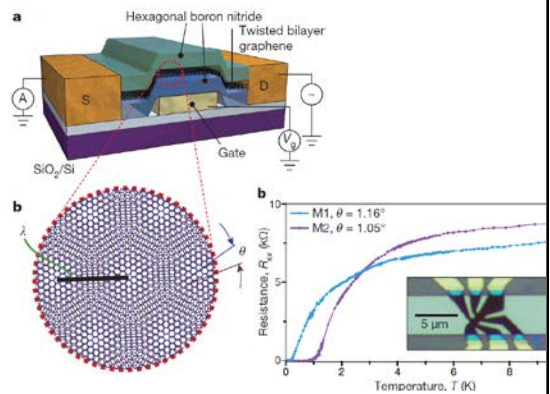


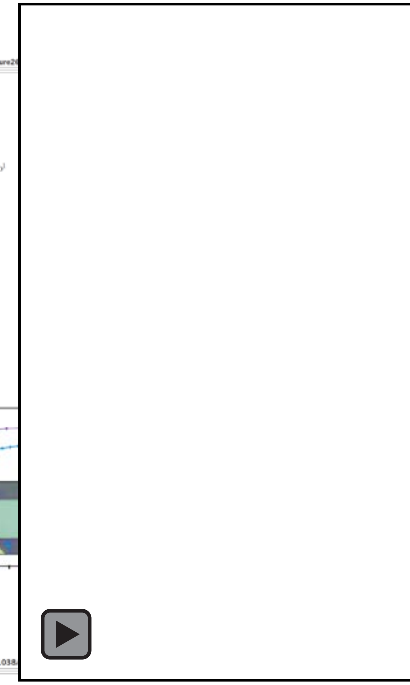
ARTICLE

doi:10.1038/nature2

Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Shiang Fang[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4] & Pablo Jarillo-Herrero[1]



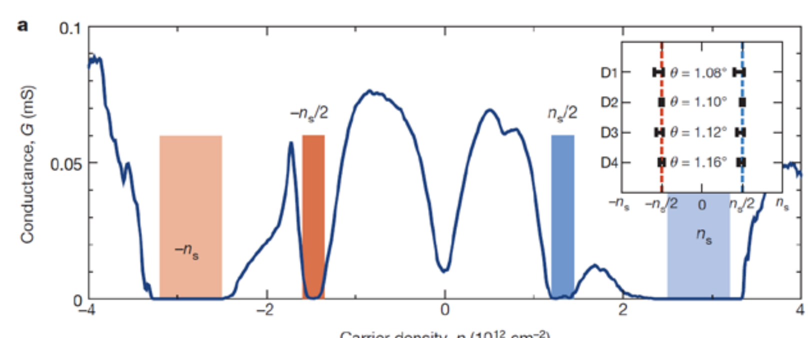


LETTER

doi:10.1038/

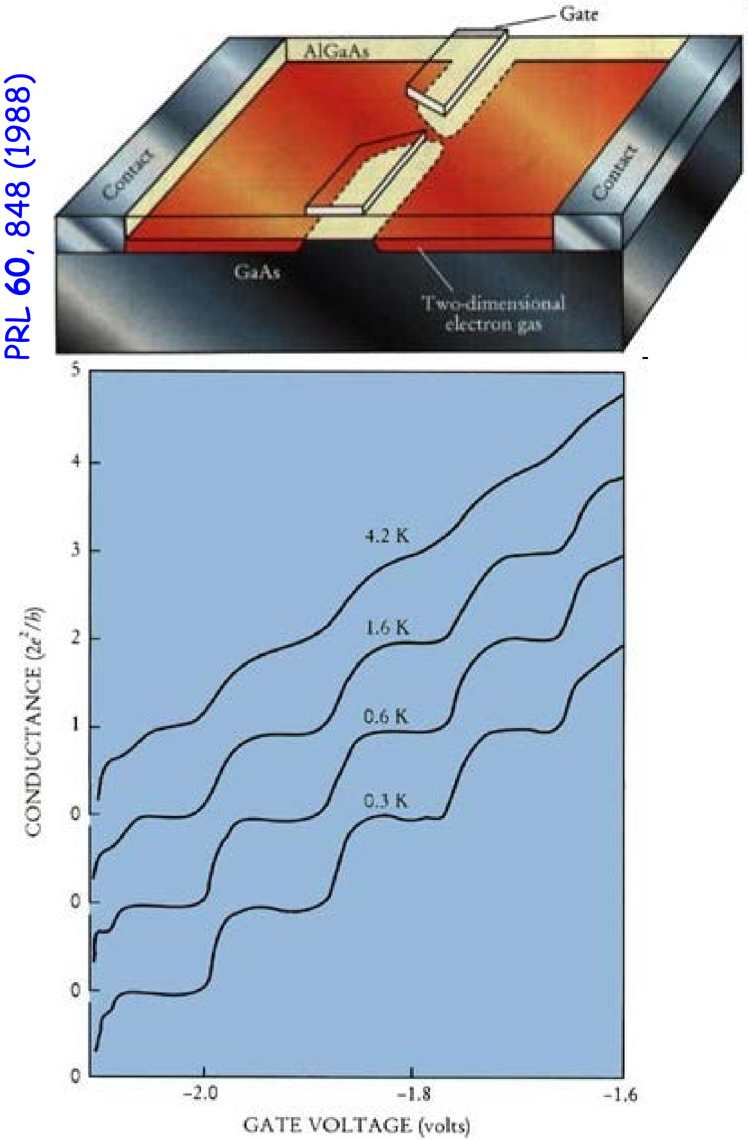
Correlated insulator behaviour at half-filling in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Ahmet Demir[1], Shiang Fang[2], Spencer L. Tomarken[1], Jason Y. Luo[1], Javier D. Sanchez-Yamagishi[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4], Ray C. Ashoori[1] & Pablo Jarillo-Herrero[1]

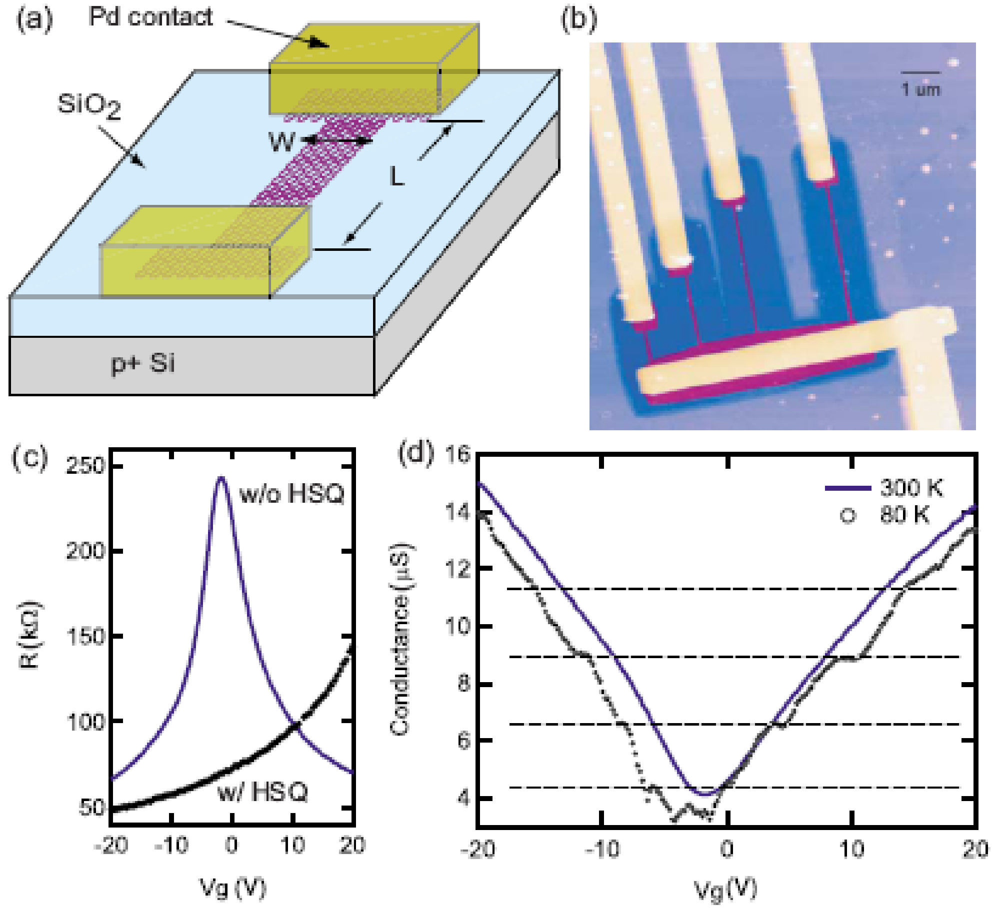


Example: Conductance Quantization

PRL **60**, 848 (1988)

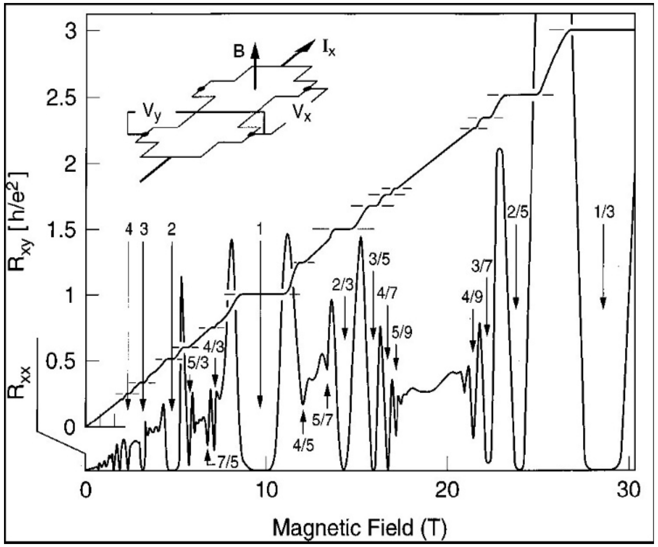


PRB **78**, 161409(R) (2008)

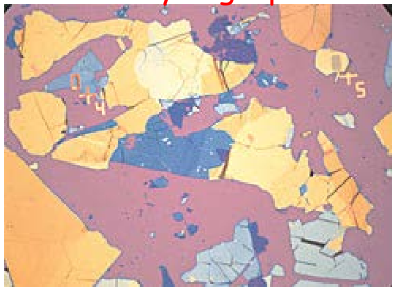


Example: Resistance Quantization in Quantum Hall Effect and Topologically-Protected Edge Currents

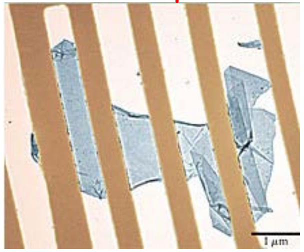
Nobel Prize in Physics 1985, 1998

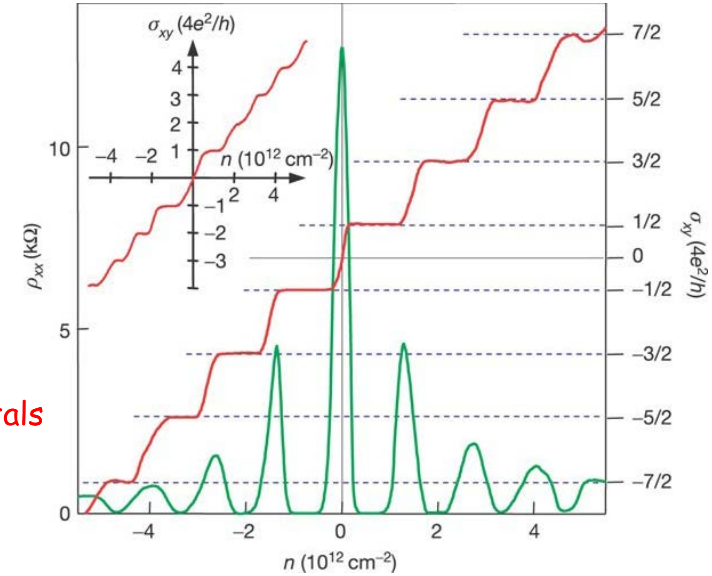


multilayer graphene



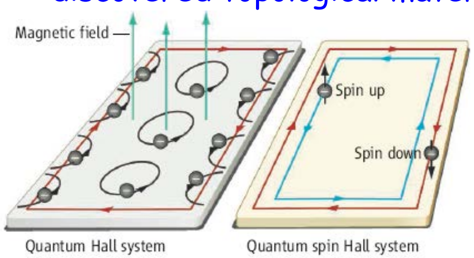
monolayer graphene is 2D electrons gas with nontrivial landscape of orbitals





Nobel Prize in Physics 2010

theoretical explanation of QHE introduces topologically protected edge (or surface in 3D) conducting states which play a key role in recently discovered topological materials



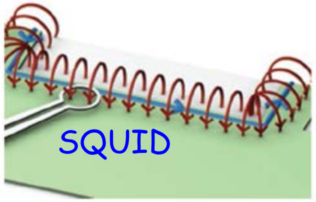

nature materials

LETTERS

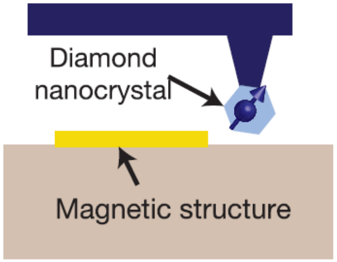
PUBLISHED ONLINE: 16 JUNE 2013 | DOI: 10.1038/NMAT3682

Imaging currents in HgTe quantum wells in the quantum spin Hall regime

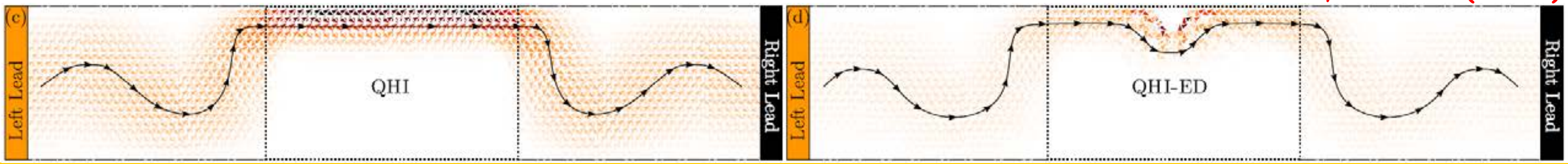
Katja C. Nowack[1,2]*, Eric M. Spanton[2,3], Matthias Baenninger[2,3], Markus König[2,3], John R. Kirtley[1], Beena Kalisky[1,4], C. Ames[5], Philipp Leubner[5], Christoph Brüne[5], Hartmut Buhmann[5], Laurens W. Molenkamp[5], David Goldhaber-Gordon[2,3] and Kathryn A. Moler[1,2,3]



future →

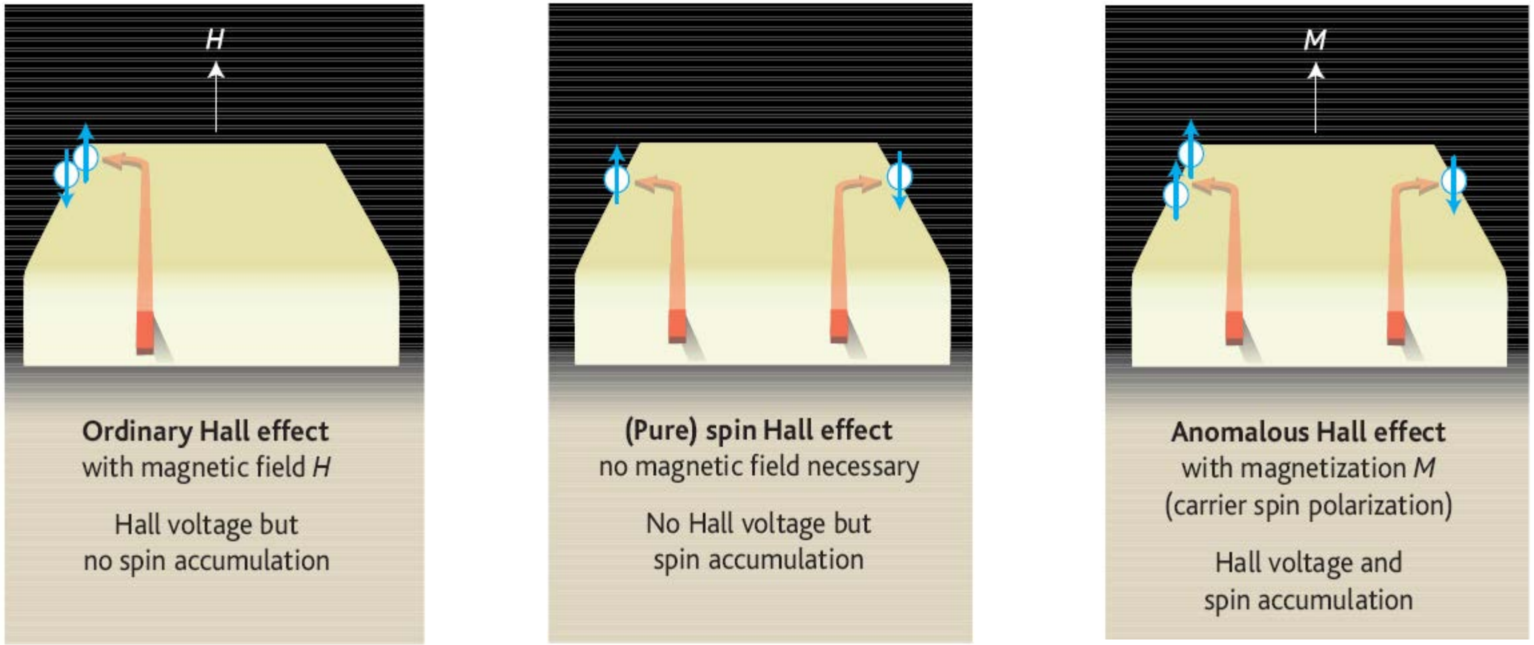


PRR **2**, 033438 (2020)

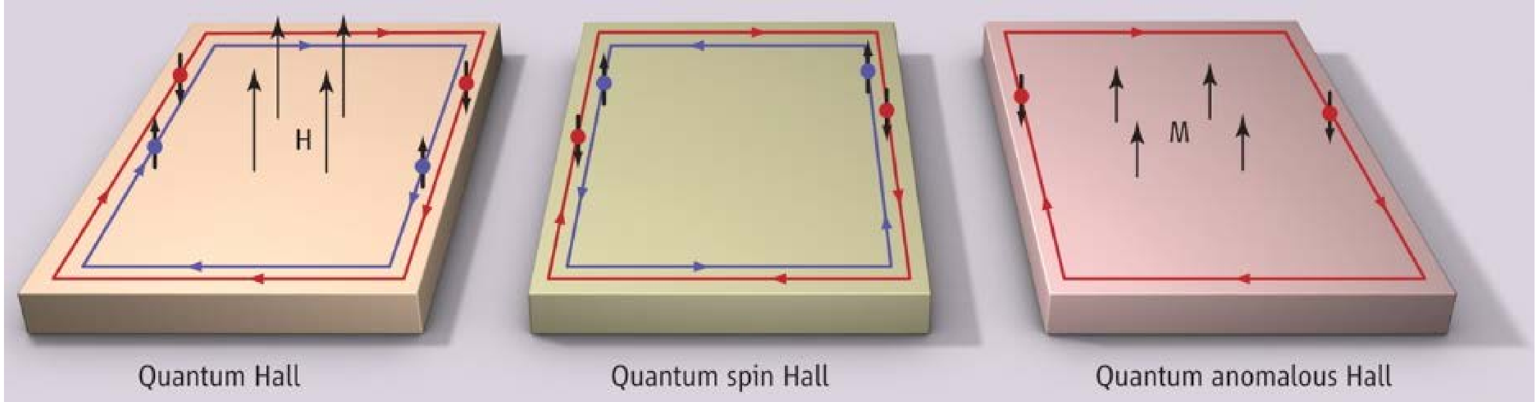


Classical and Quantum Hall Trio

Classical



Quantum

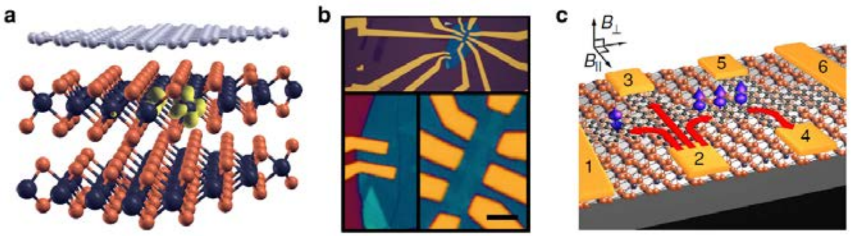


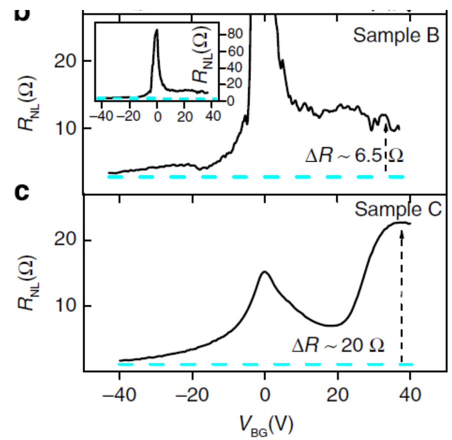
Example: Nonlocal Resistance in Multiterminal Graphene-Based van der Waals Heterostructures

❑Direct and inverse spin Hall effect

theory: PRL **117**, 176602 (2016)

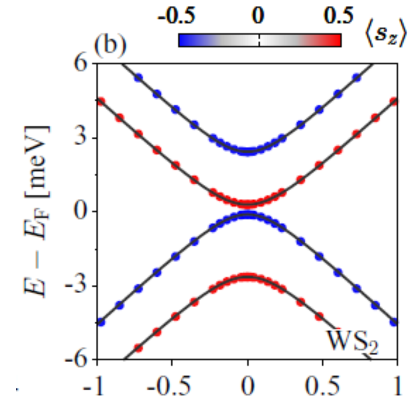
G/WS_2





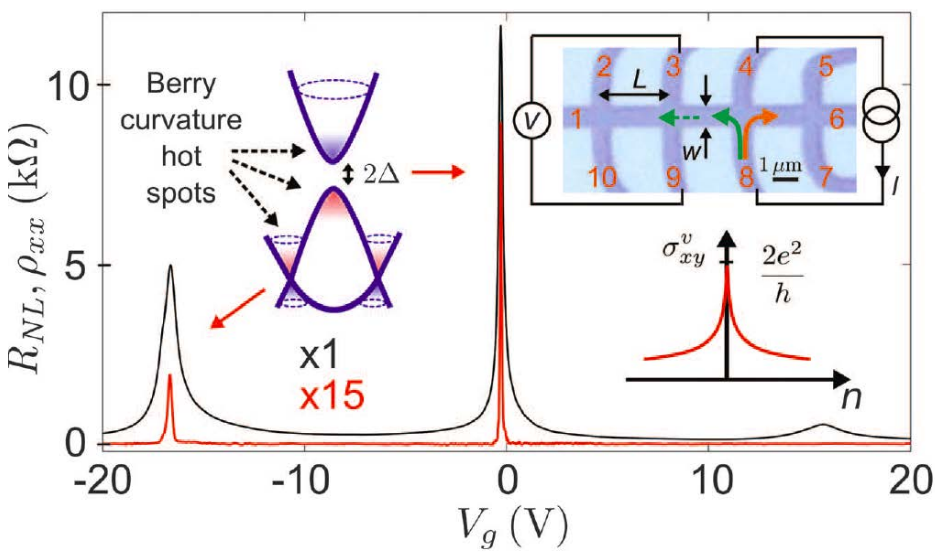
Nat. Commun. **5**, 4875 (2014)

PRB **93**, 155104 (2016)

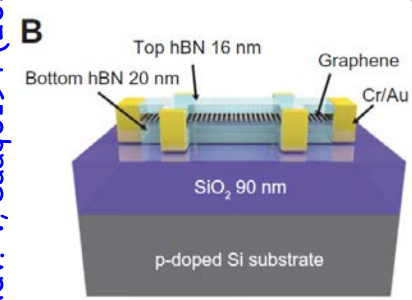


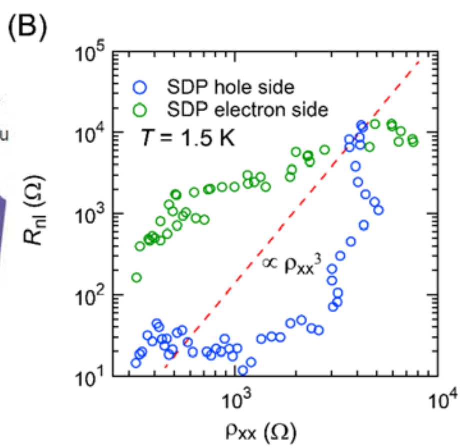
❑Direct and inverse valley Hall effect in graphene/hBN

Science **346**, 448 (2014)



Sci. Adv. **4**, eaaq0194 (2018)





theory: J. Phys.: Mater. **1**, 0150061 (2018)

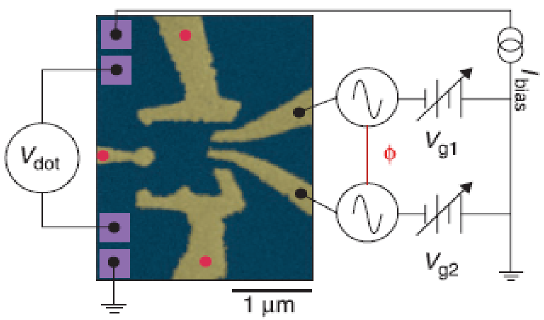
Example: Quantum Pumping of Charge and Spin

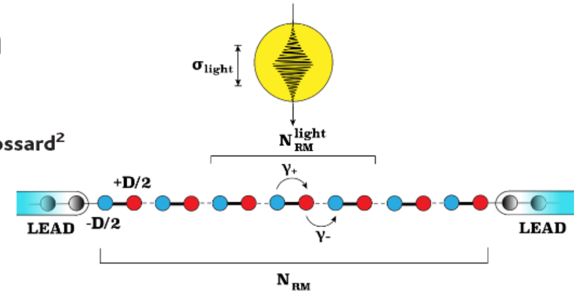
CHARGE

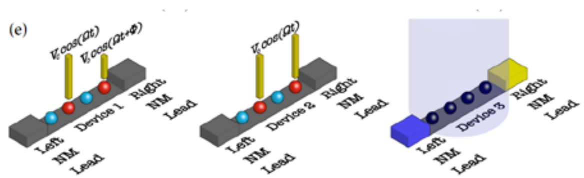
Science **283**, 1905 (1999)

An Adiabatic Quantum Electron Pump

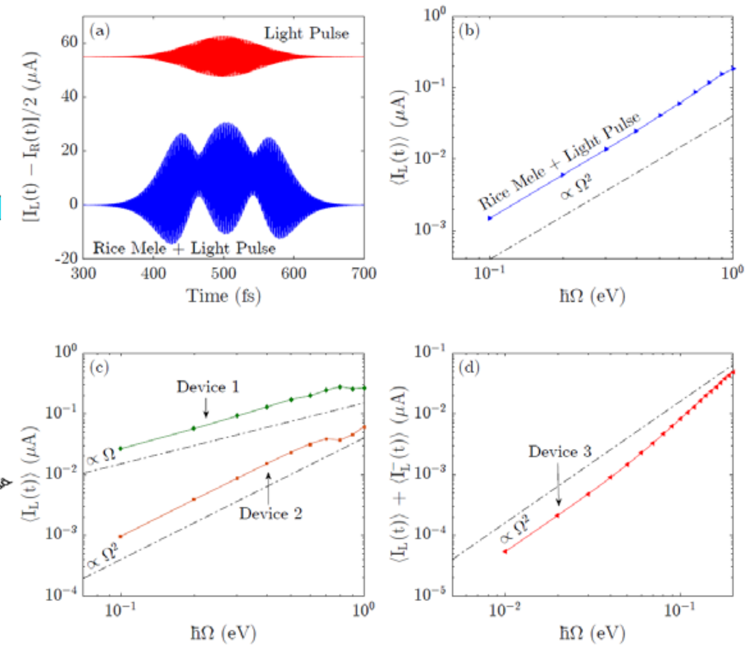
M. Switkes,[1] C. M. Marcus,[1*] K. Campman,[2] A. C. Gossard[2]





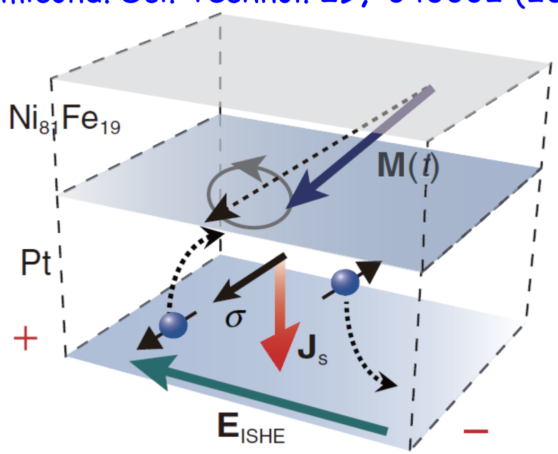


J. Phys.: Mater. **2**, 025004 (2019)

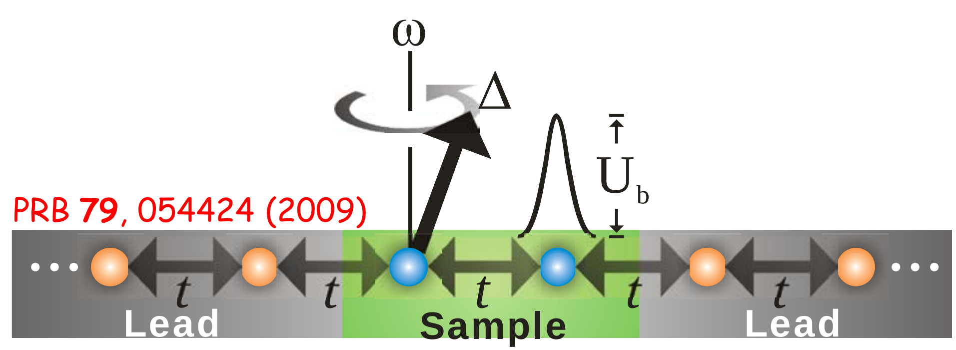


SPIN

Semicond. Sci. Technol. **29**, 043002 (2014)

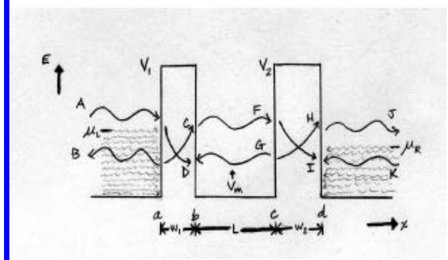


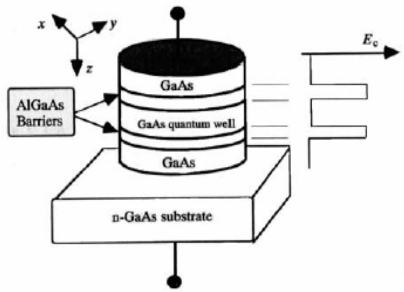
PRB **79**, 054424 (2009)

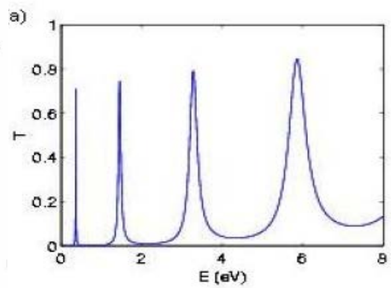


Example: Good and Bad Consequences of Quantum Tunneling for Electronics and Spintronics

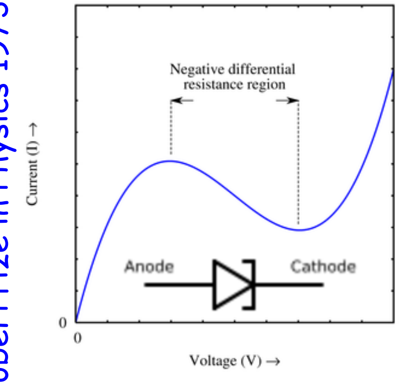
Good



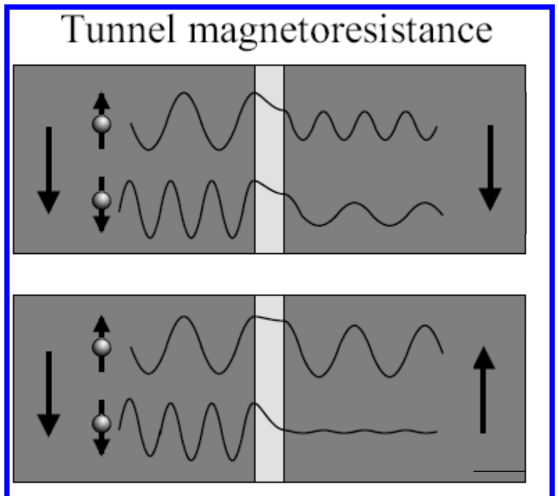




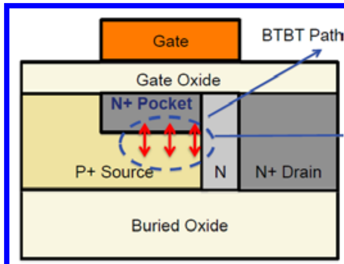
Nobel Prize in Physics 1973

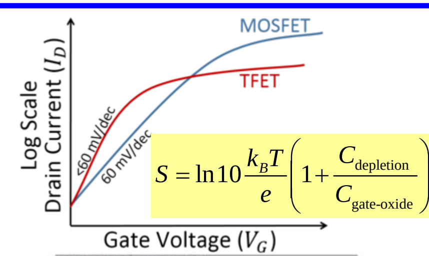


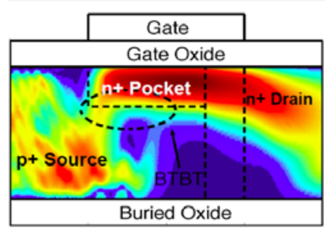
Good

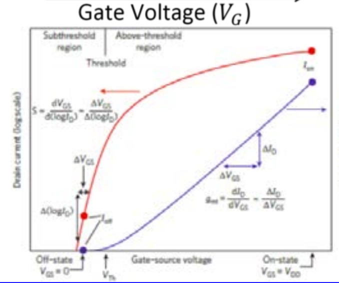


Good

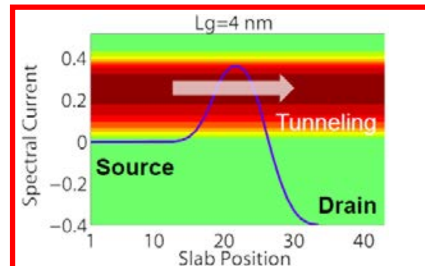


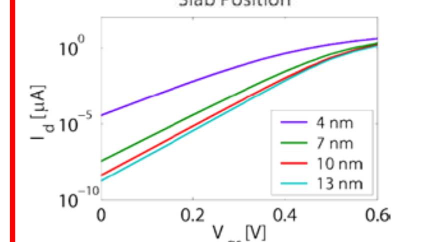




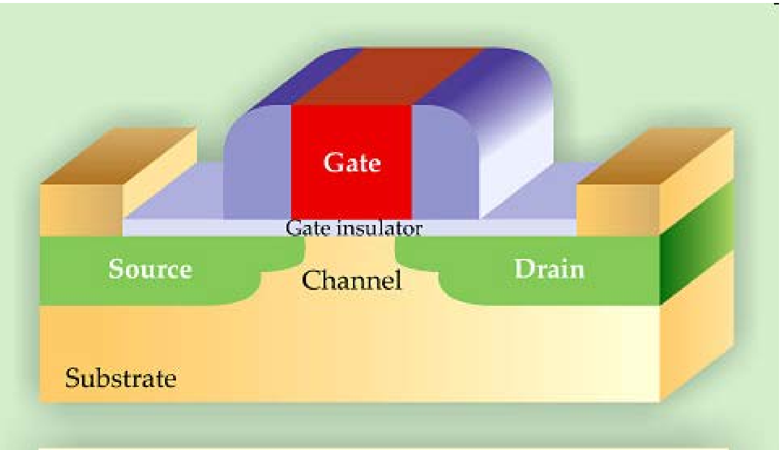


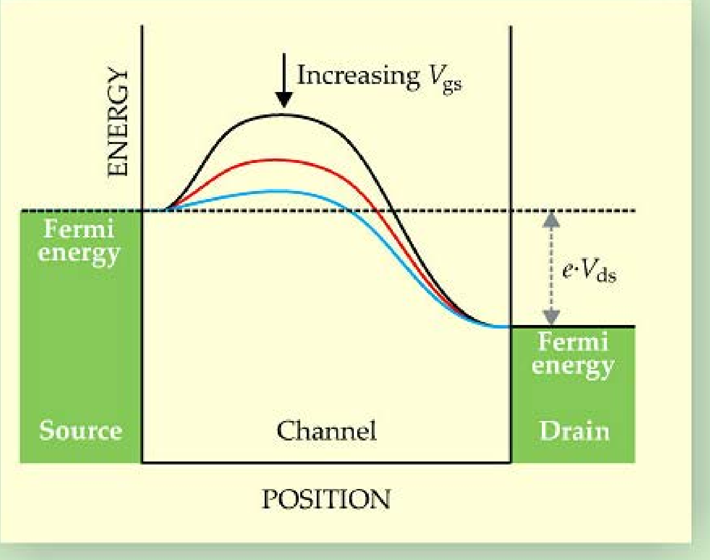
Bad

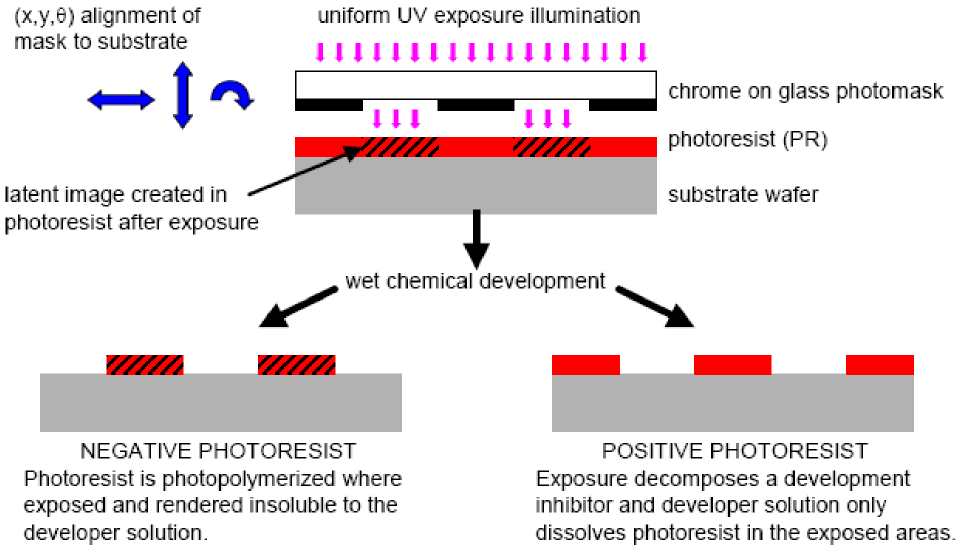


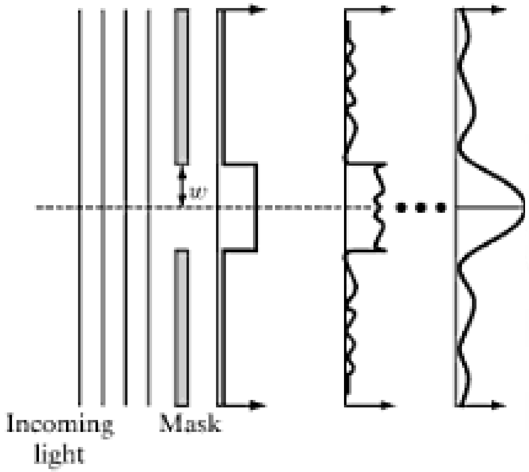


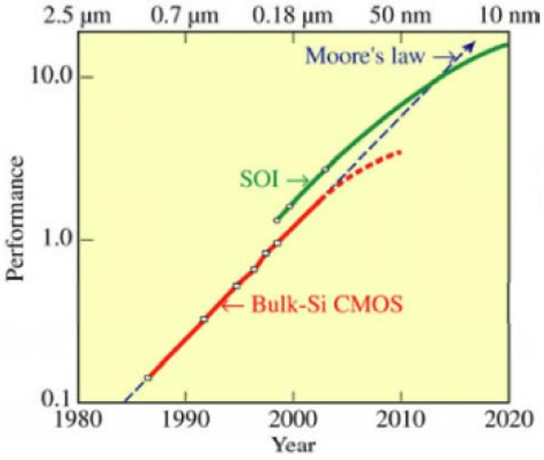
Limits of Top-Down Approach in Conventional Electronics



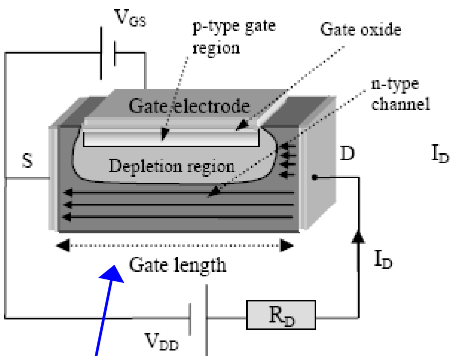


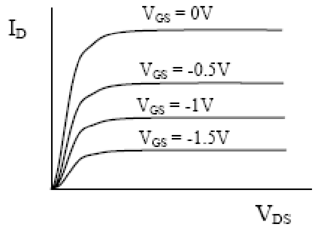


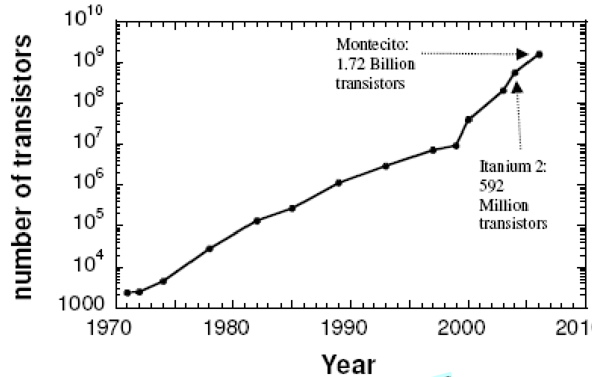


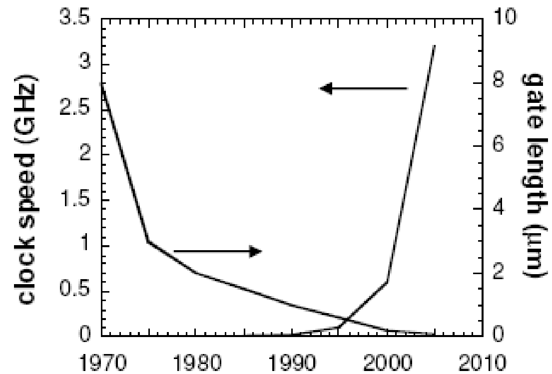


Fundamental Quantum Effects at the Nanoscale Act Against Moore's Law for Conventional FETs



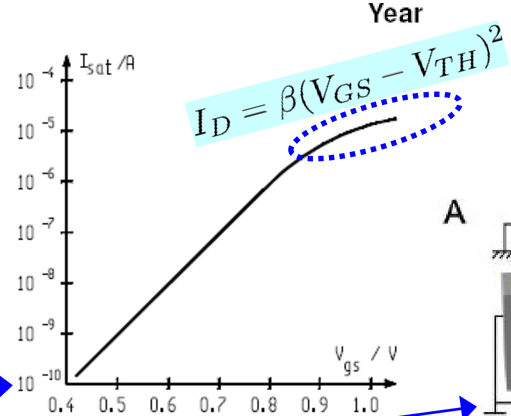




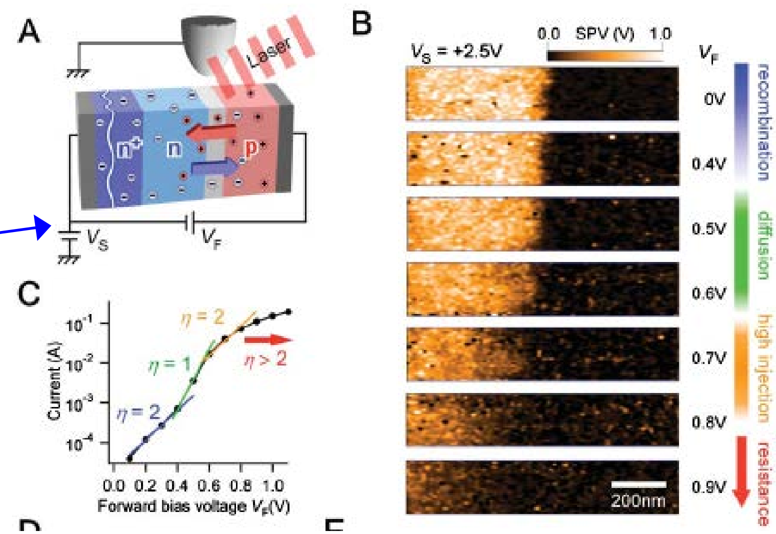


Nonscaling effects at nanometer MOSFETs:

- quantum tunneling of carriers through the gate insulator and through the body-to-drain junction
- dependence of sub-threshold behavior on temperature
- discrete doping effects
- power dissipated in various leakage mechanisms

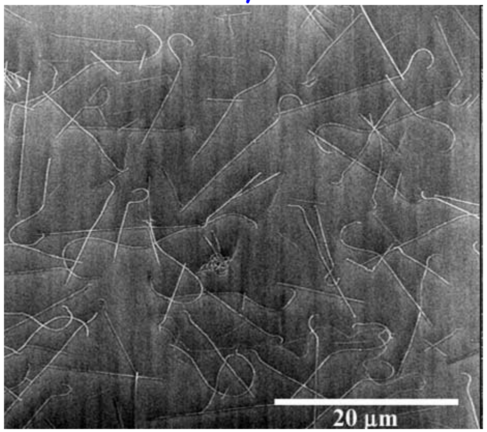


PRL **98**, 026802 (2007)

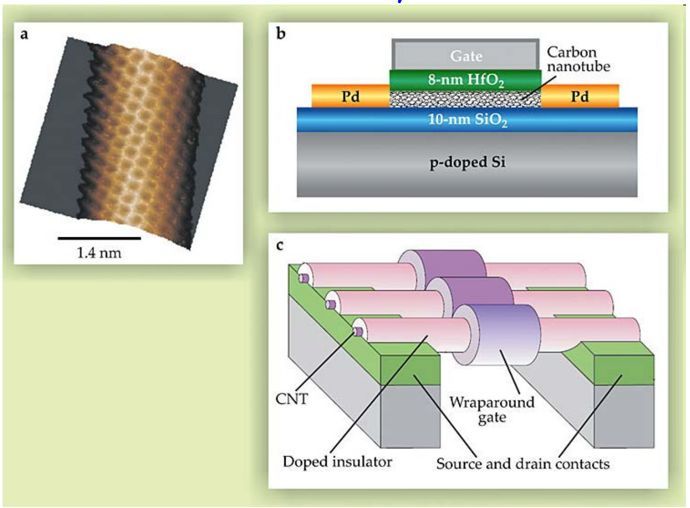


Nanotechnology:
Molecular Electronics via Bottom-Up Approach

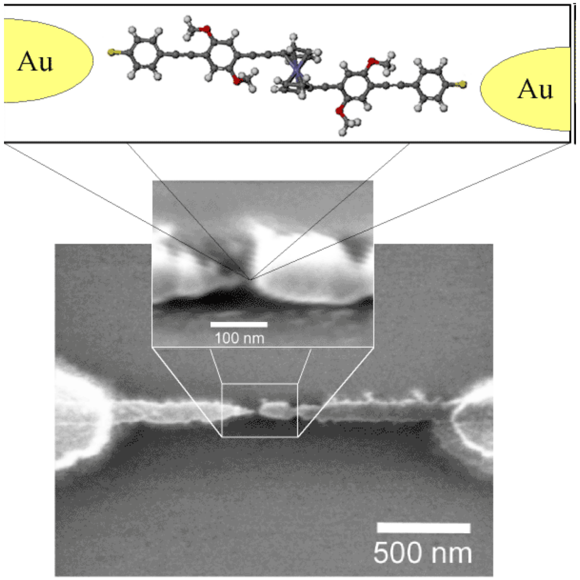
Fuhrer Lab, Monash U.

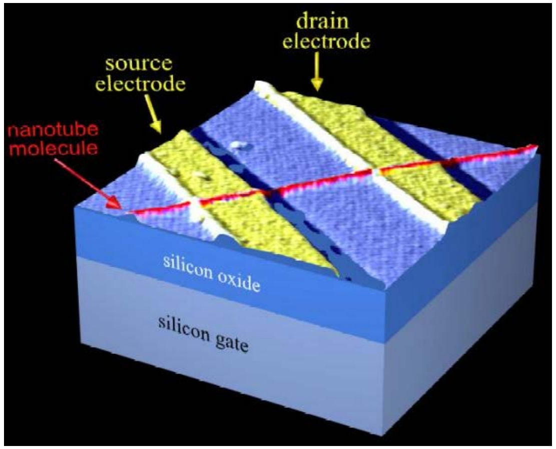


Avouris Lab, IBM

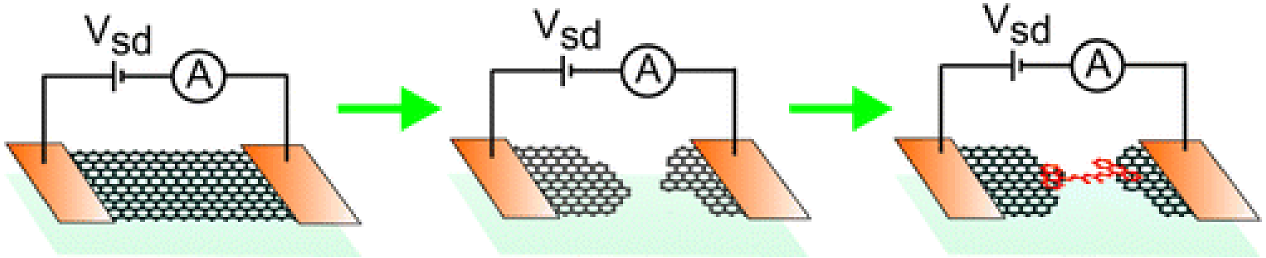


Ruitenbek Lab, Leiden U.
Venkataraman Lab, Columbia U.

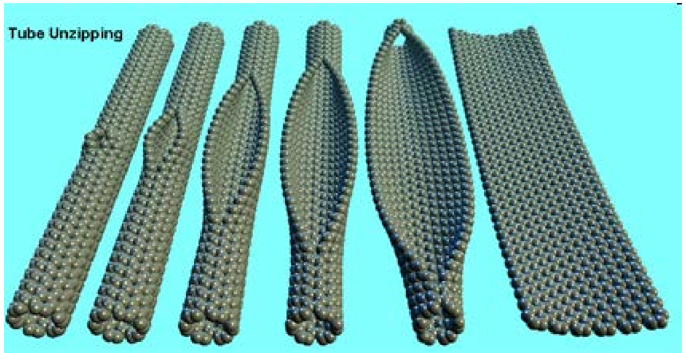


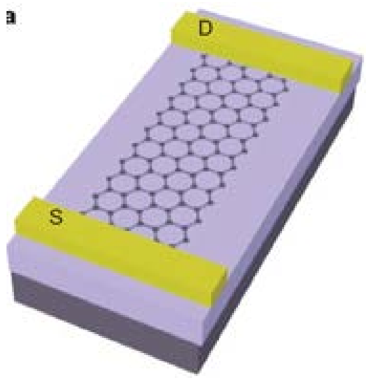


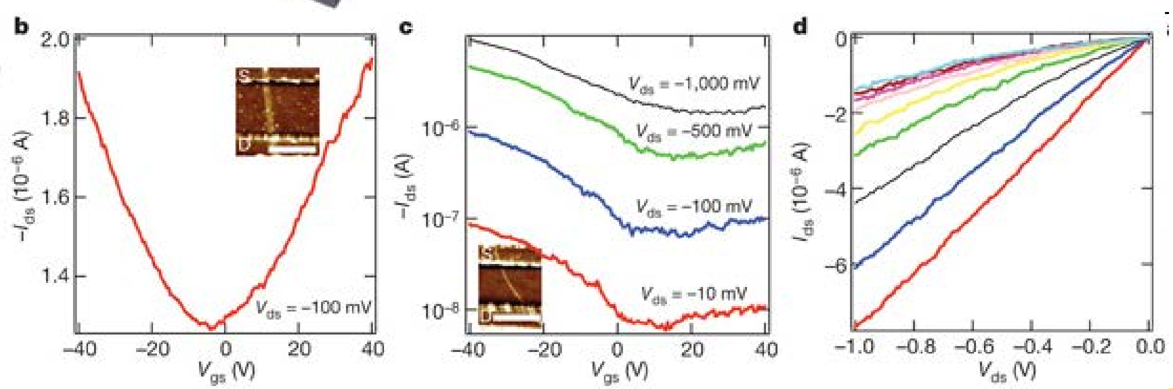
van der Zant Lab, Delft (Nano Lett. 2011)

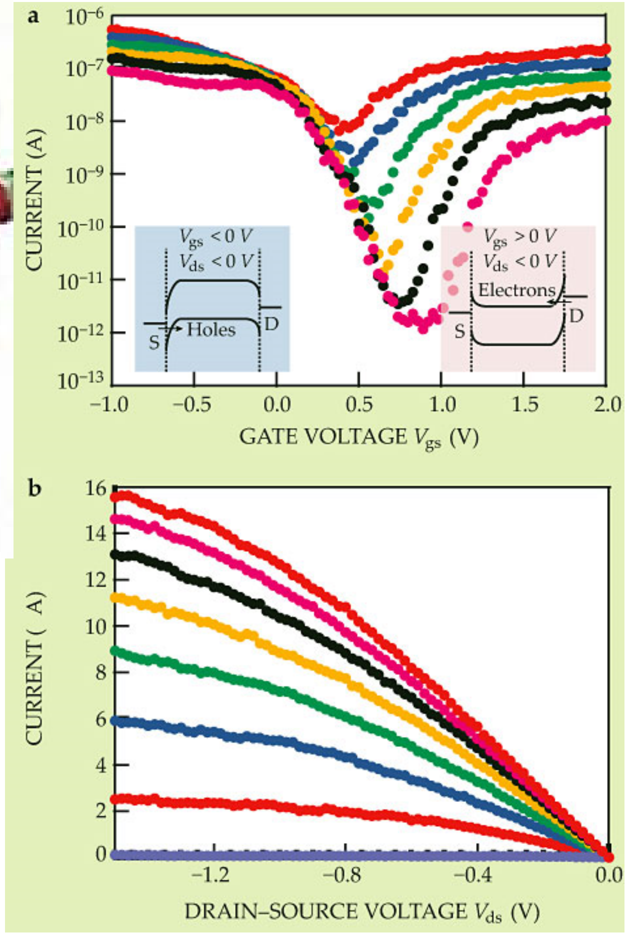


Nanotechnology : Nanoelectronics with GNRs and CNTs

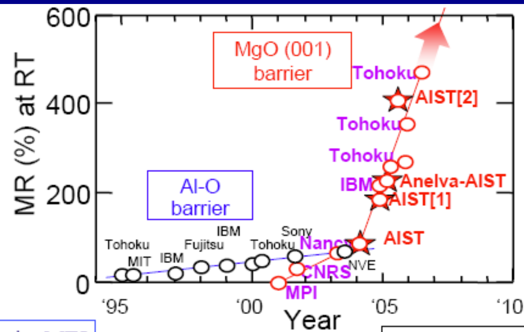


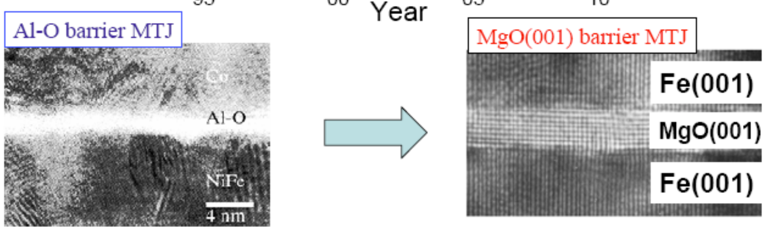




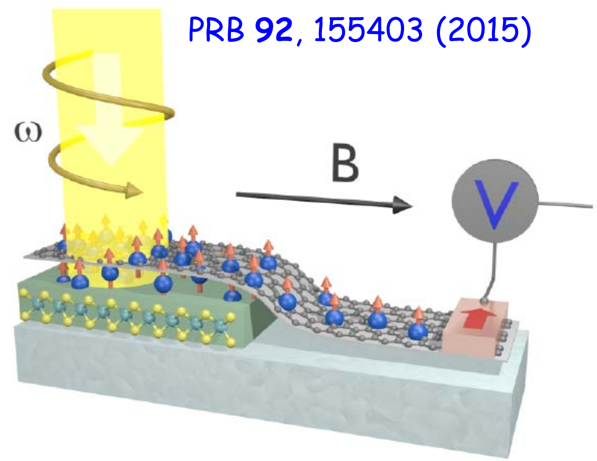


Nanotechnology: Spintronics and Optospintronics





A. C. C. Yu, et al., *JJAP* 40, 5058 (2001) [1] S. Yuasa, Y. S. et al, *Nature Materials*, 3(2004)868.



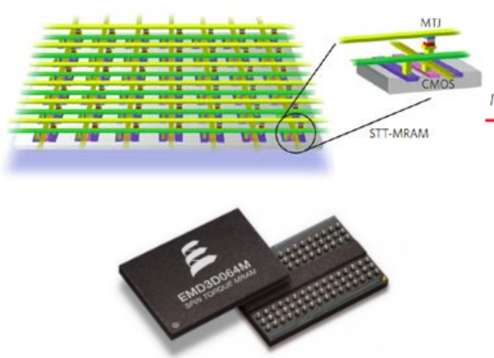
nature materials

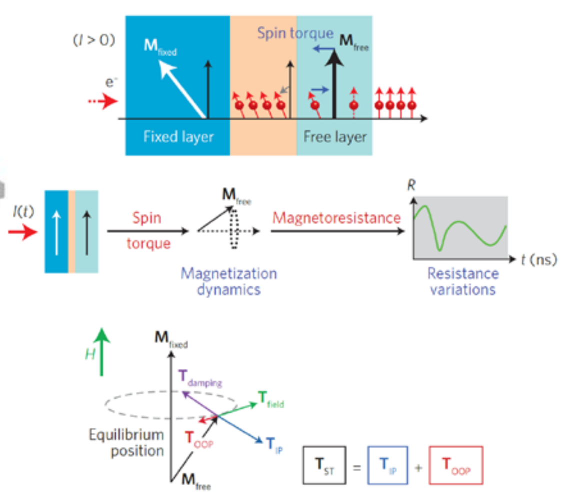
PROGRESS ARTICLE

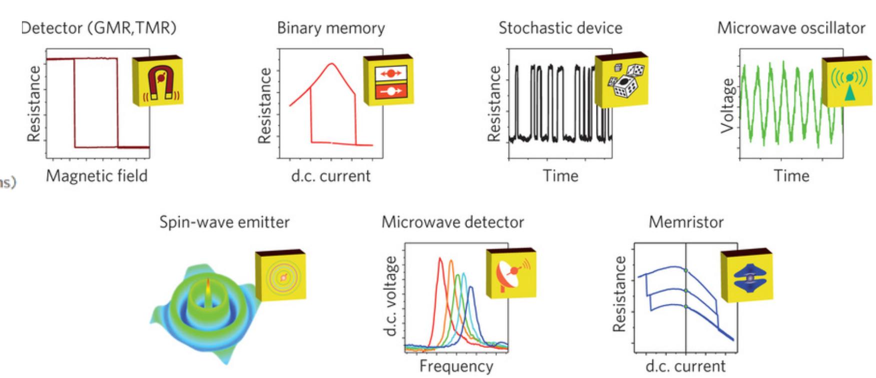
PUBLISHED ONLINE: 17 DECEMBER 2013 | DOI: 10.1038/NMAT3823

Spin-torque building blocks

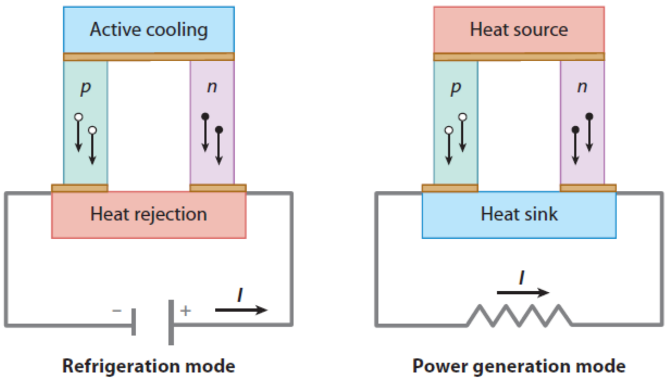
N. Locatelli, V. Cros and J. Grollier*



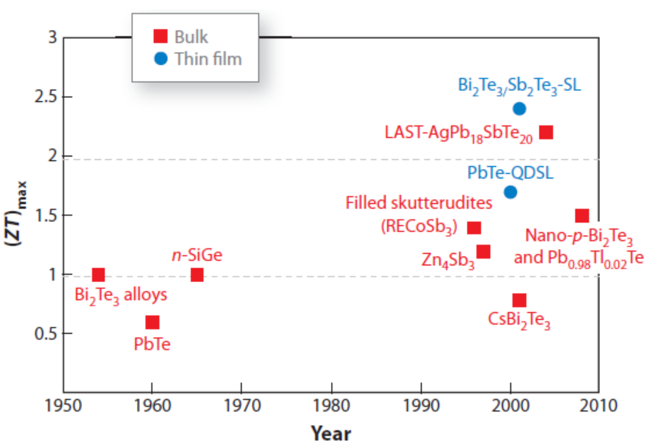


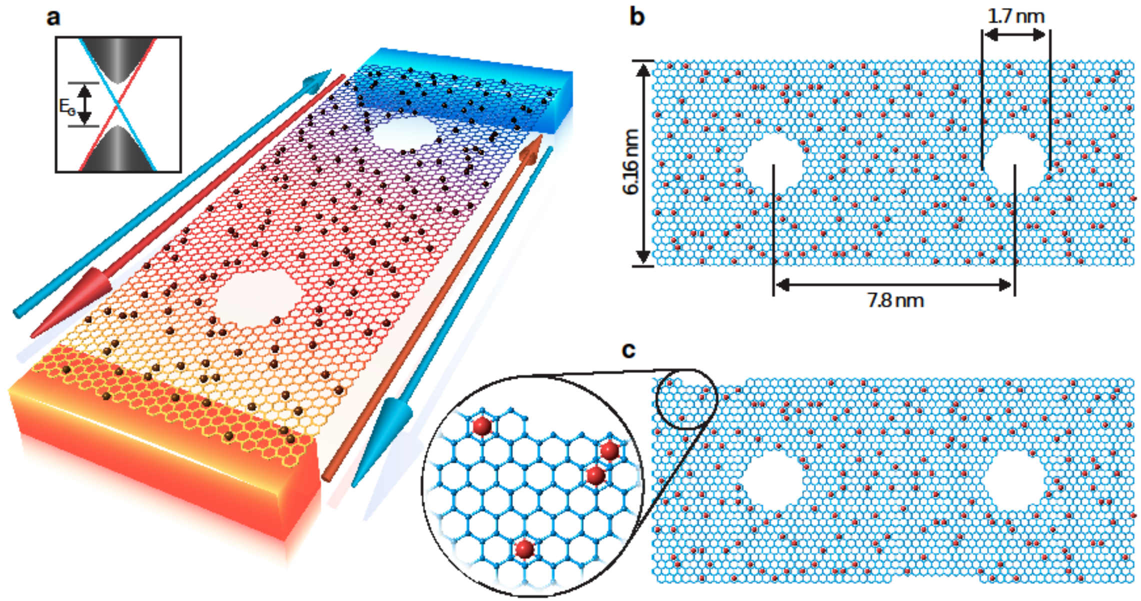


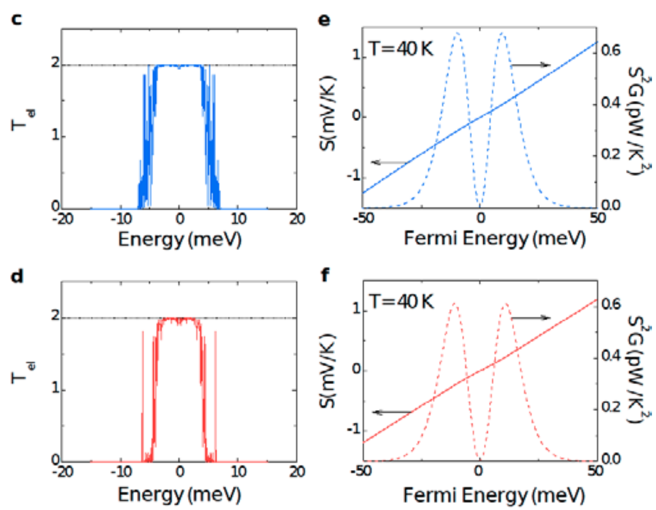
Nanotechnology: Nanoscale Thermoelectrics

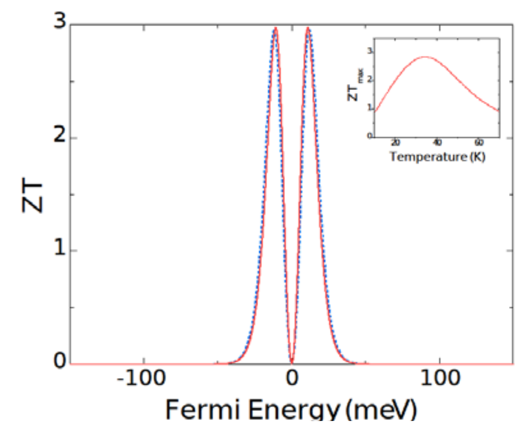


$$ZT = \frac{S^2GT}{\kappa_{\mathrm{el}} + \kappa_{\mathrm{ph}}}$$



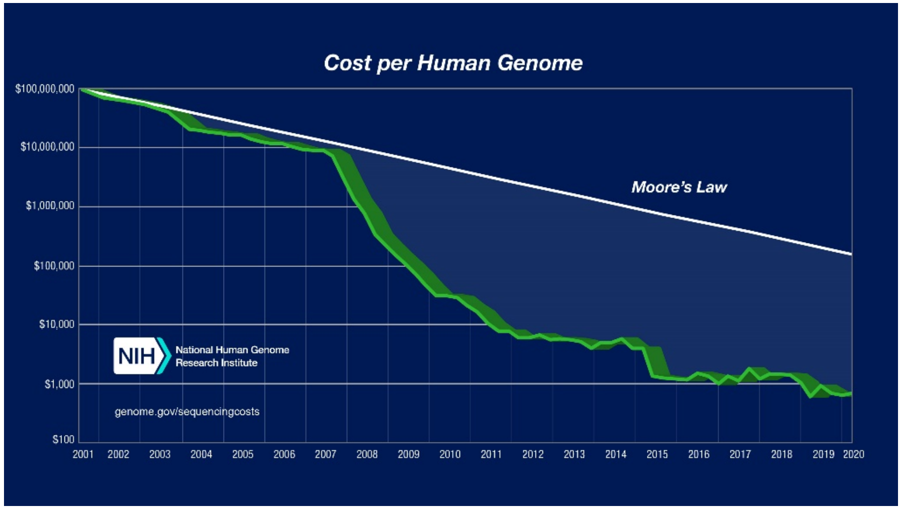






Nano Lett. 14, 3779 (2014)

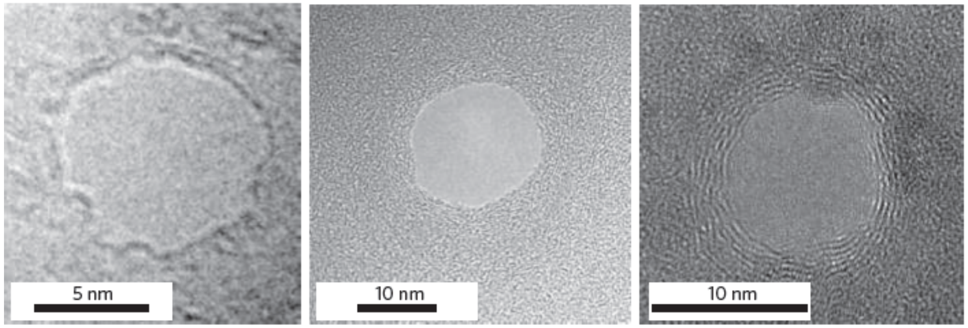
Nanotechnology: Nano-Bio Interface



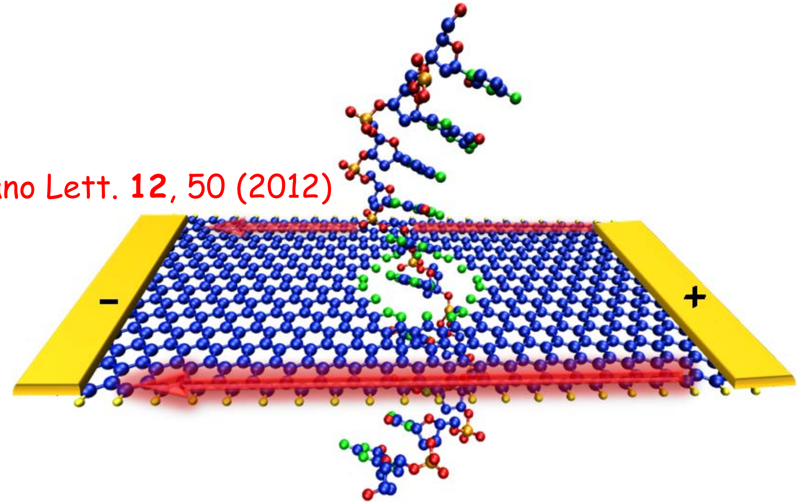
nature nanotechnology | FOCUS | REVIEW ARTICLE
PUBLISHED ONLINE: 3 FEBRUARY 2016 | DOI: 10.1038/NNANO.2015.307

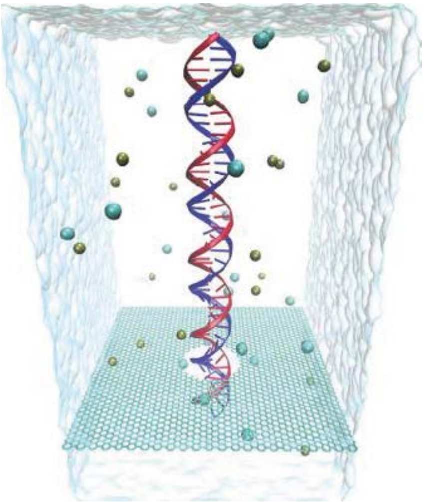
Graphene nanodevices for DNA sequencing

Stephanie J. Heerema and Cees Dekker*



Nano Lett. **12**, 50 (2012)





Branches of Nanophysics & Nanotechnology