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New electronics from the surface chemistry of low dimensional nanostructures

Jim Greer

Molecular Electro-Opto-Spintronics - SPICE
Mainz, Germany
October 15, 2019

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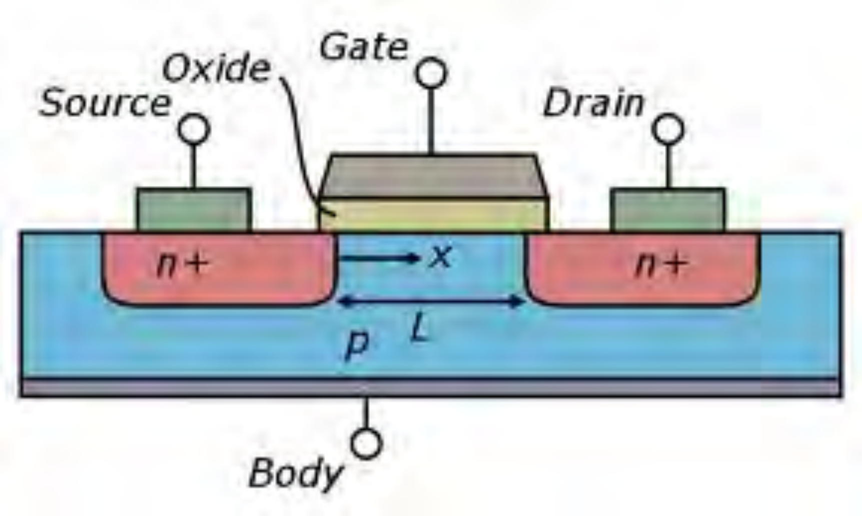
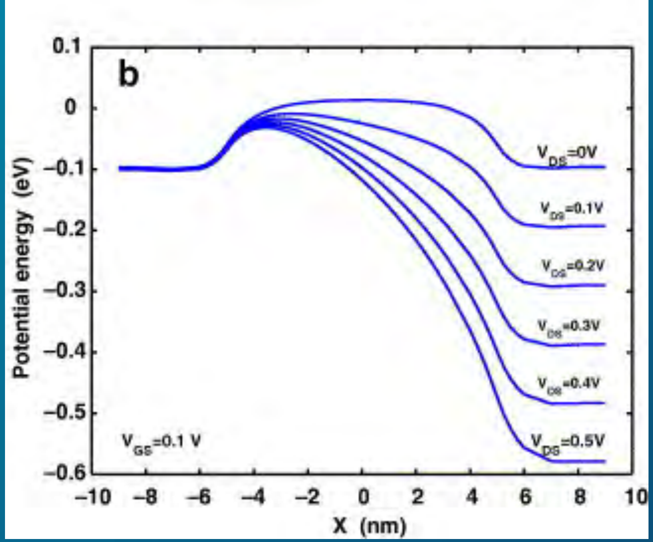
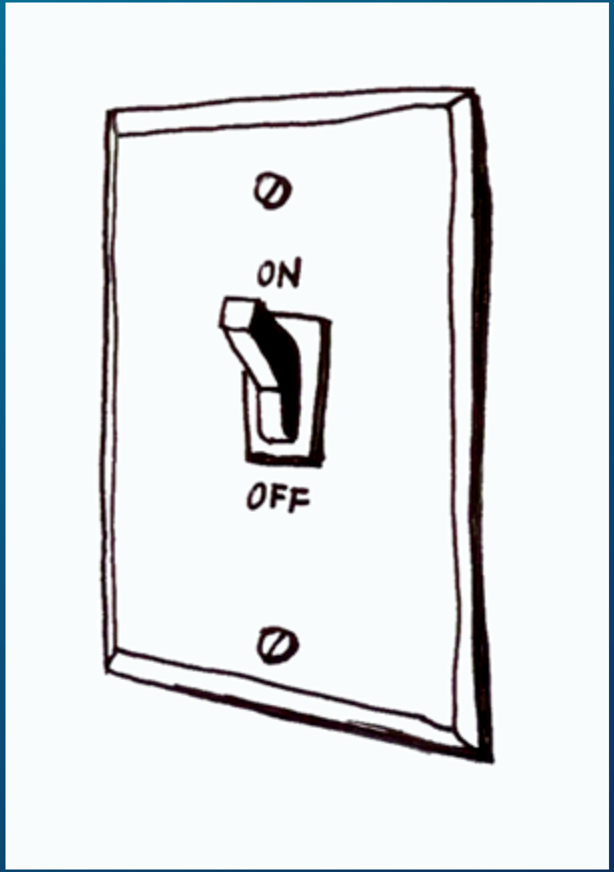
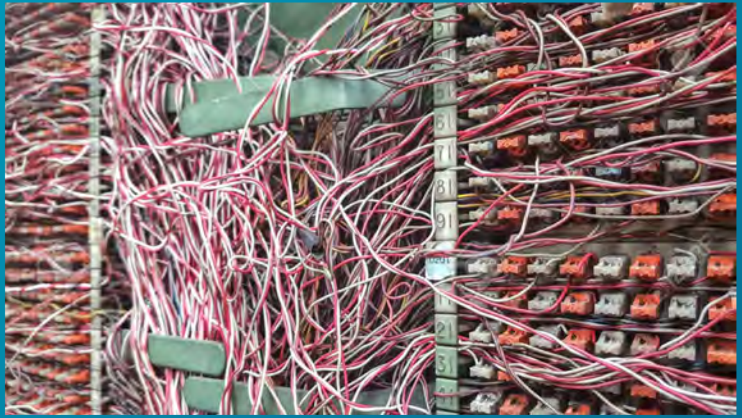
Field effect transistor



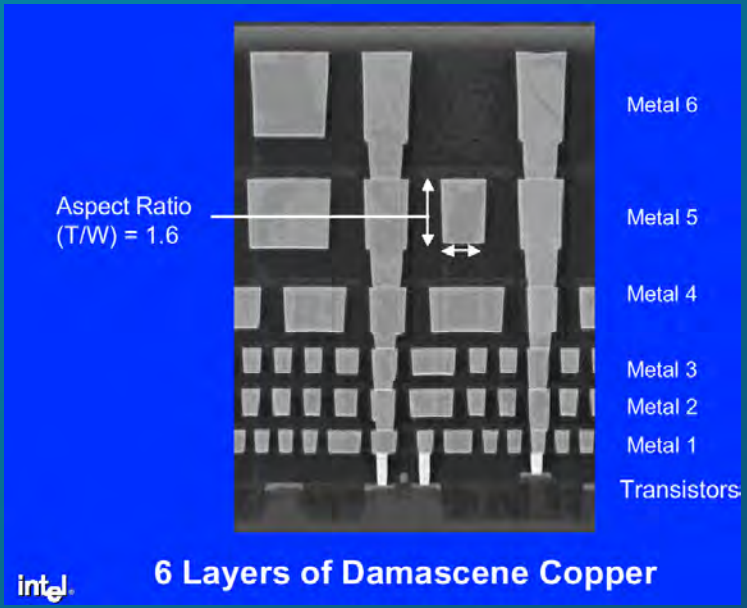




The first integrated circuits or microchips

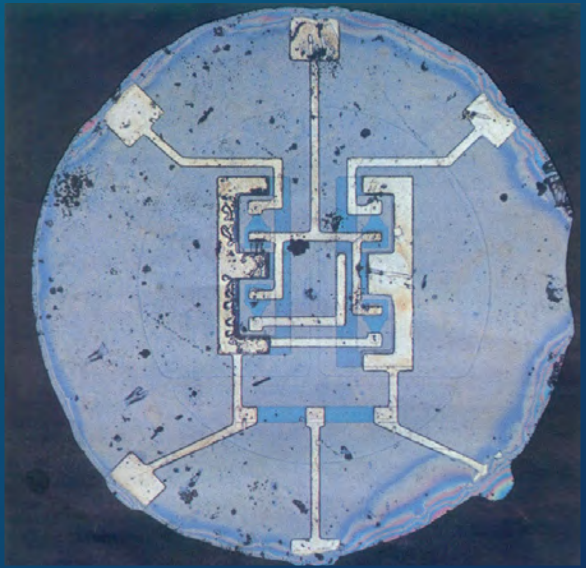


The wiring problem



Nobel Prize in Physics 2000

Jack Kilby: Inventor of the first integrated circuit at Texas Instruments in 1958

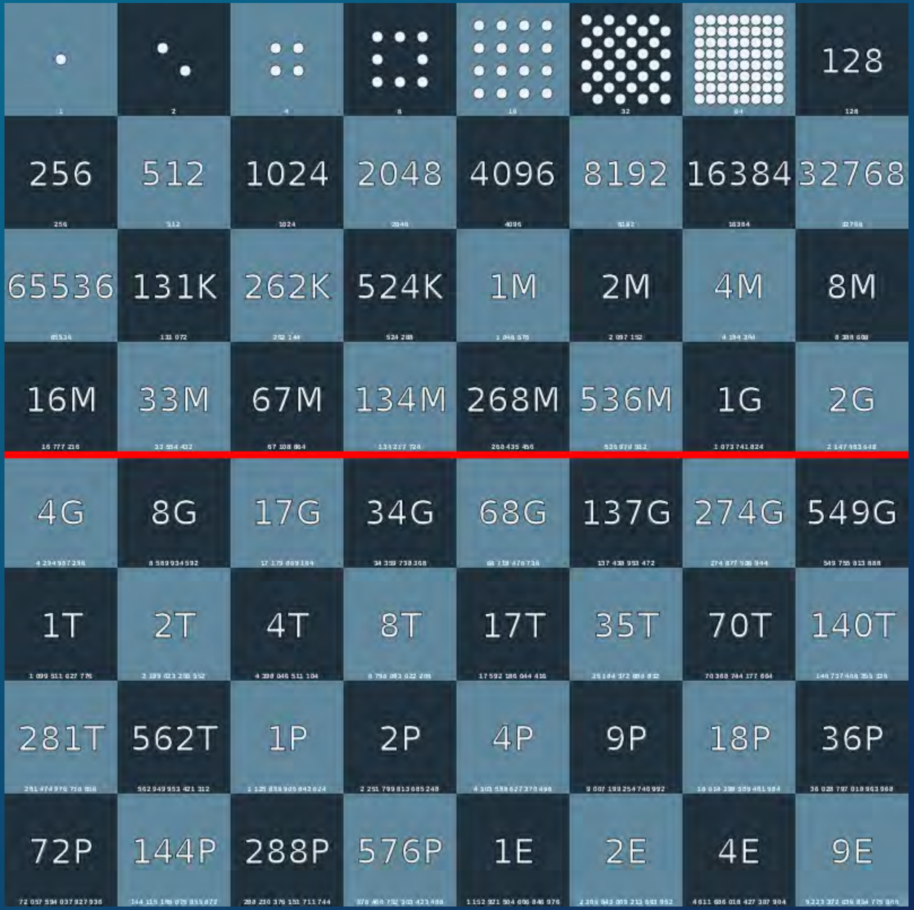


Fairchild 1959: Flip-flop, world's first monolithic chip

Robert Noyce co-credited with invention of ICs

Rice and the chessboard: scaling & doubling

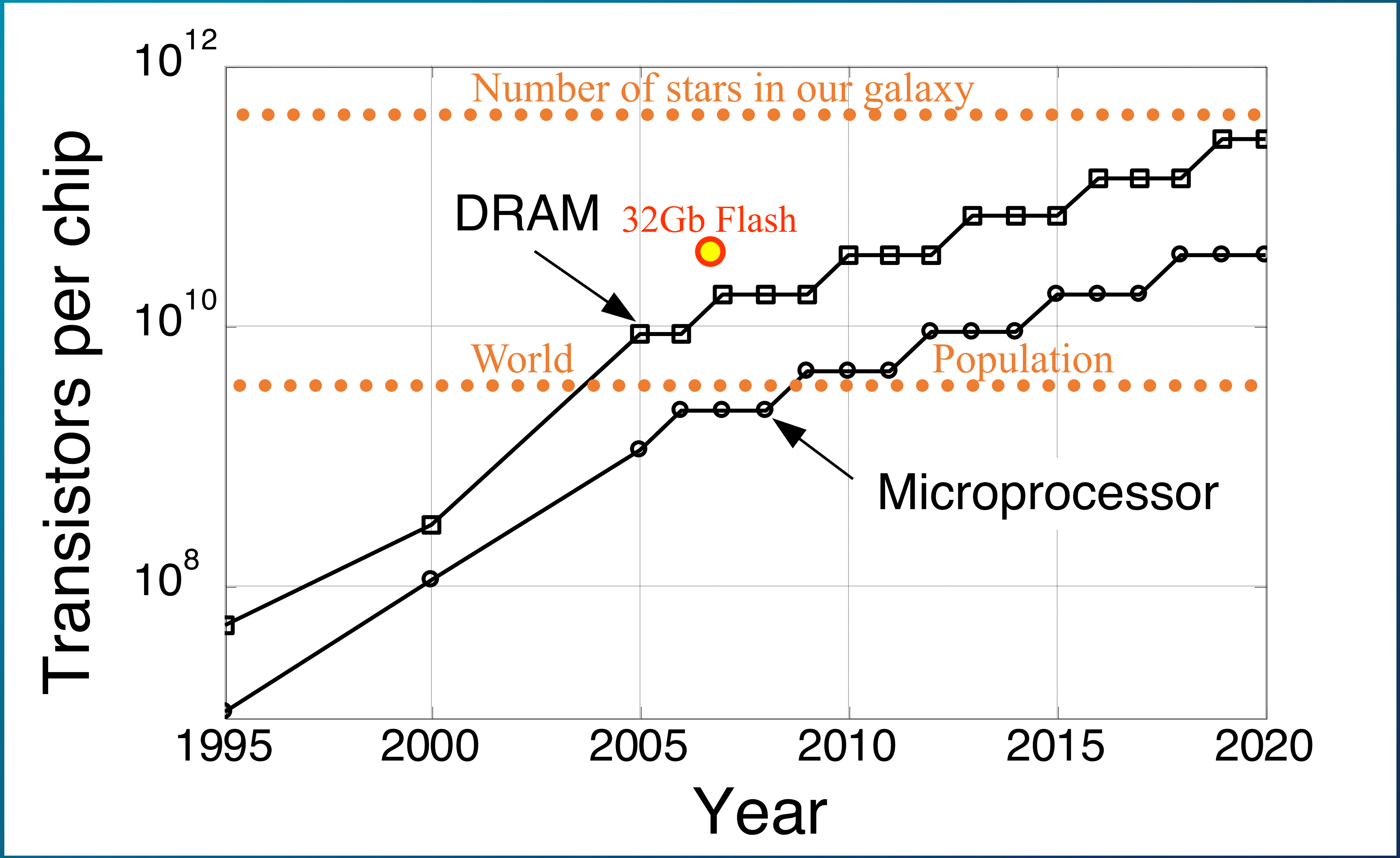
K=kilo	1,000
M=mega	1,000,000
G=giga	1,000,000,000
T=tera	1,000,000,000,000
P=peta	1,000,000,000,000,000
E=exa	1,000,000,000,000,000,000



1	2	4	8	16	32	64	128
256	512	1024	2048	4096	8192	16384	32768
65536	131K	262K	524K	1M	2M	4M	8M
16M	33M	67M	134M	268M	536M	1G	2G
4G	8G	17G	34G	68G	137G	274G	549G
1T	2T	4T	8T	17T	35T	70T	140T
281T	562T	1P	2P	4P	9P	18P	36P
72P	144P	288P	576P	1E	2E	4E	9E

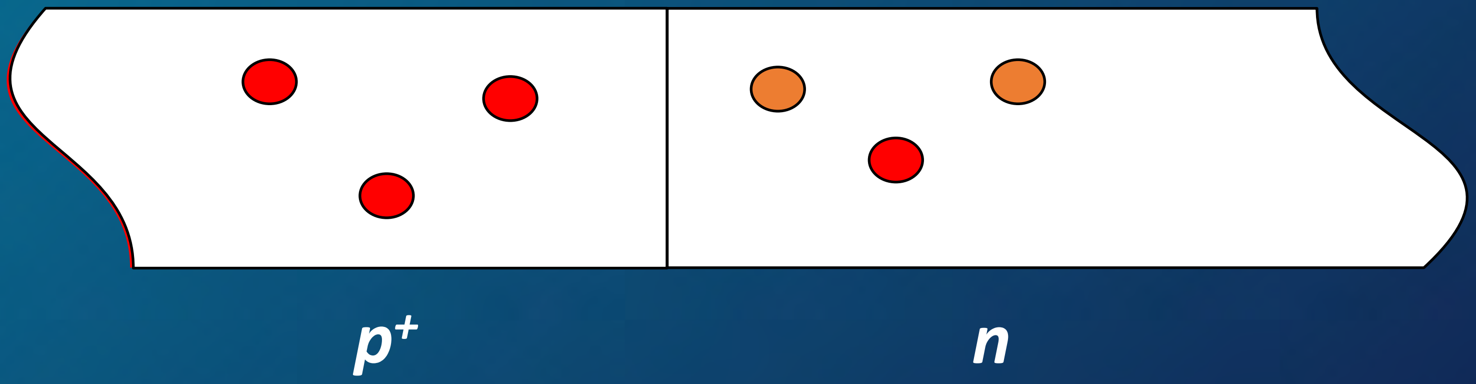
9,223,372,036,854,775,808 grains of rice on the last square

How many switches are in a modern microchip?

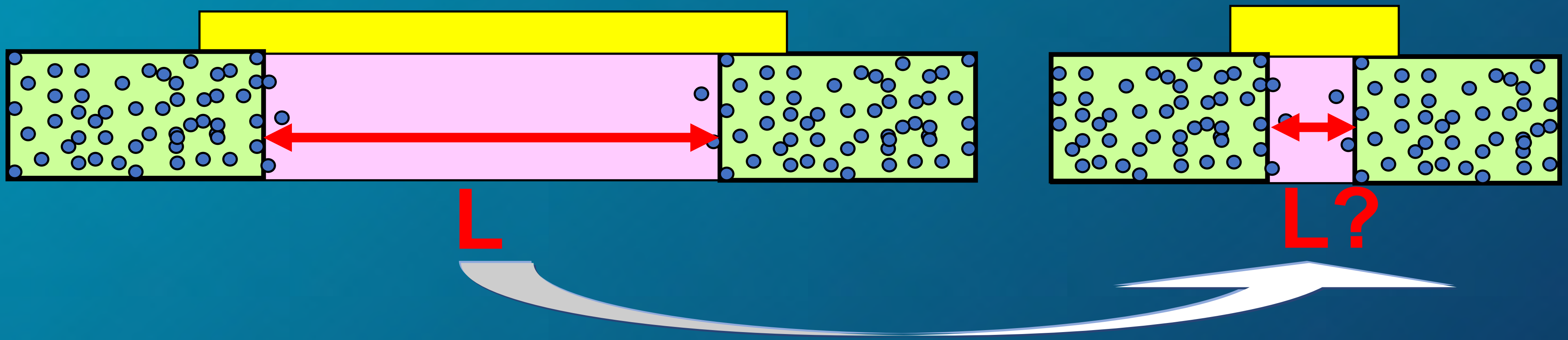


Next big challenge: the atomic resolution of matter

NW dimensions/ nm^3	Atoms/ nanowire volume	Atoms/ nanowire length	Dopant atoms/ nanowire
60x20x20	1,200,000	222	1200
30x10x10	150,000	111	150
15x5x5	18,750	55	~20
6x2x2	1,200	22	~1

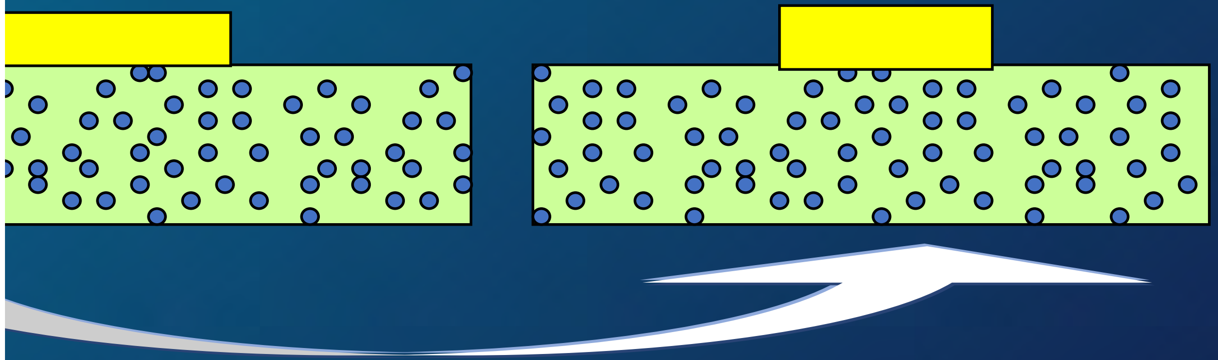


Junctions in a MOSFET required?



"Ultrashort channel"
(<10nm)

"Junctionless"



nature nanotechnology

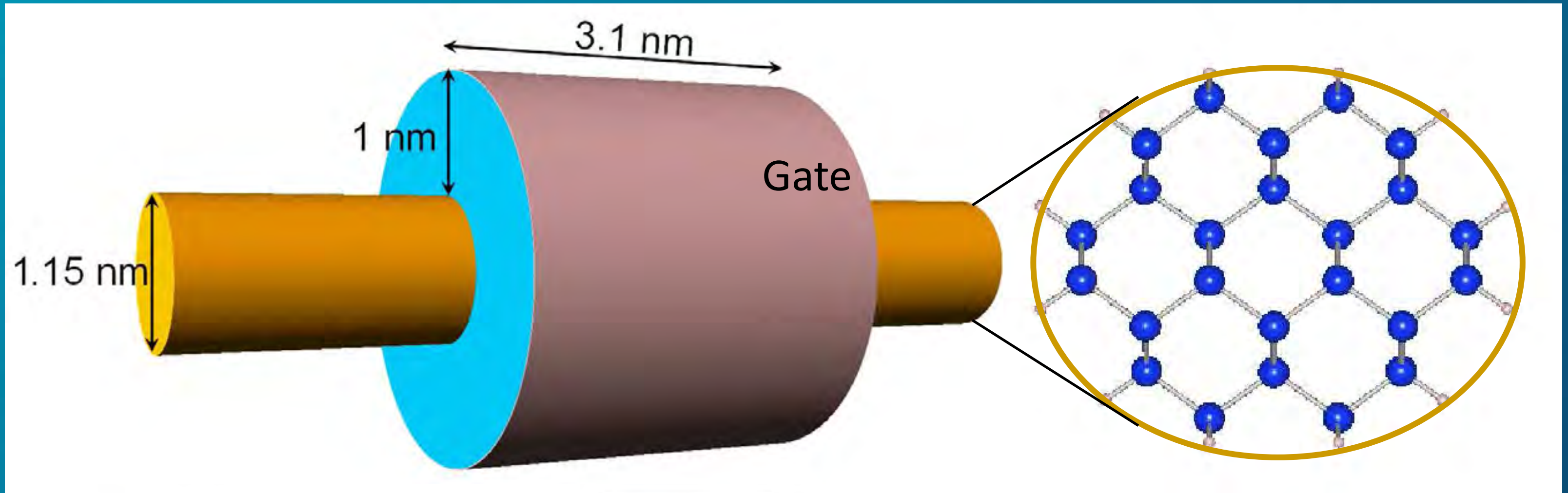
ARTICLES

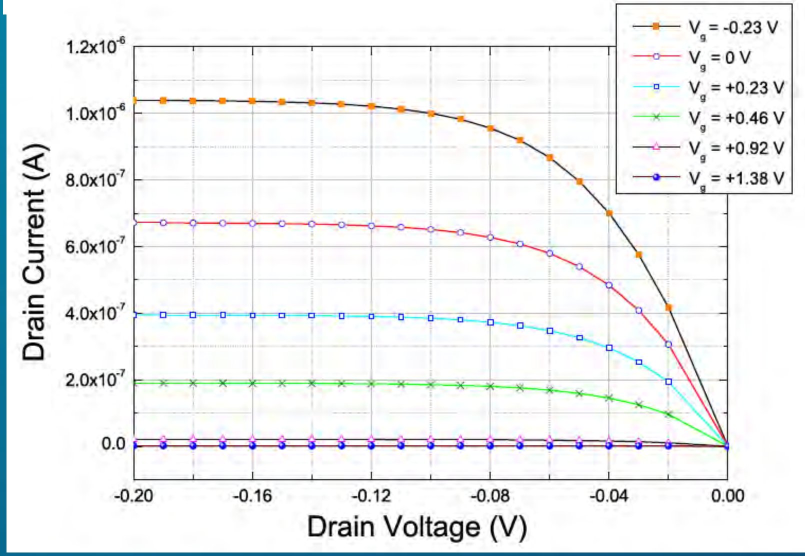
PUBLISHED ONLINE: 21 FEBRUARY 2010 | DOI: 10.1038/NNANO.2010.15

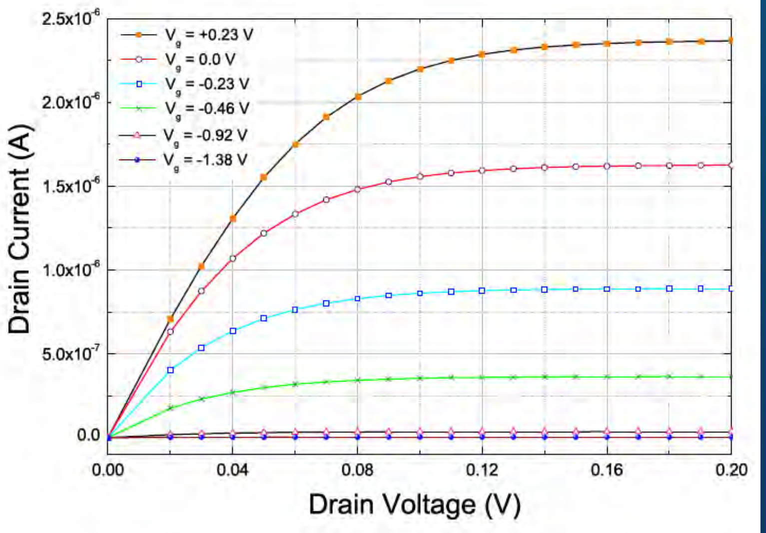
Nanowire transistors without junctions

Jean-Pierre Colinge*, Chi-Woo Lee, Aryan Afzalian[†], Nima Dehdashti Akhavan, Ran Yan, Isabelle Ferain, Pedram Razavi, Brendan O'Neill, Alan Blake, Mary White, Anne-Marie Kelleher, Brendan McCarthy and Richard Murphy

How small can you make it?







The **physics** of a junctionless transistor are **valid** to a few nm

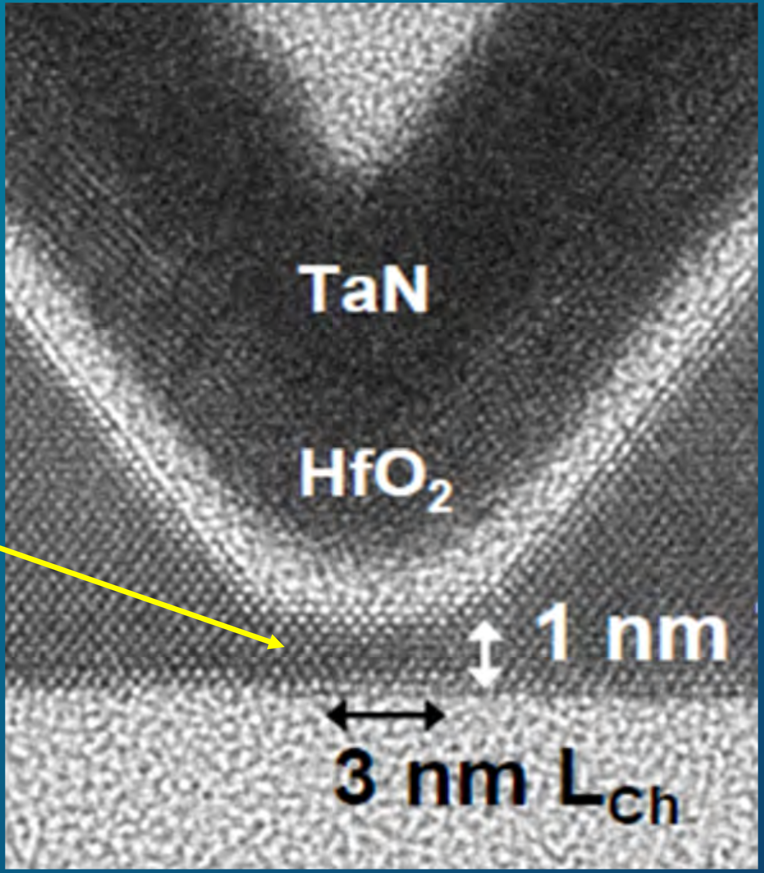
If you can make it, it will work

... but it still requires **accurate placement** of a **few dopant** atoms

L. Ansari, B. Feldman, G. Fagas, J.-P. Colinge, J.C. Greer, APL, 2010

3 nm gate junctionless transistor

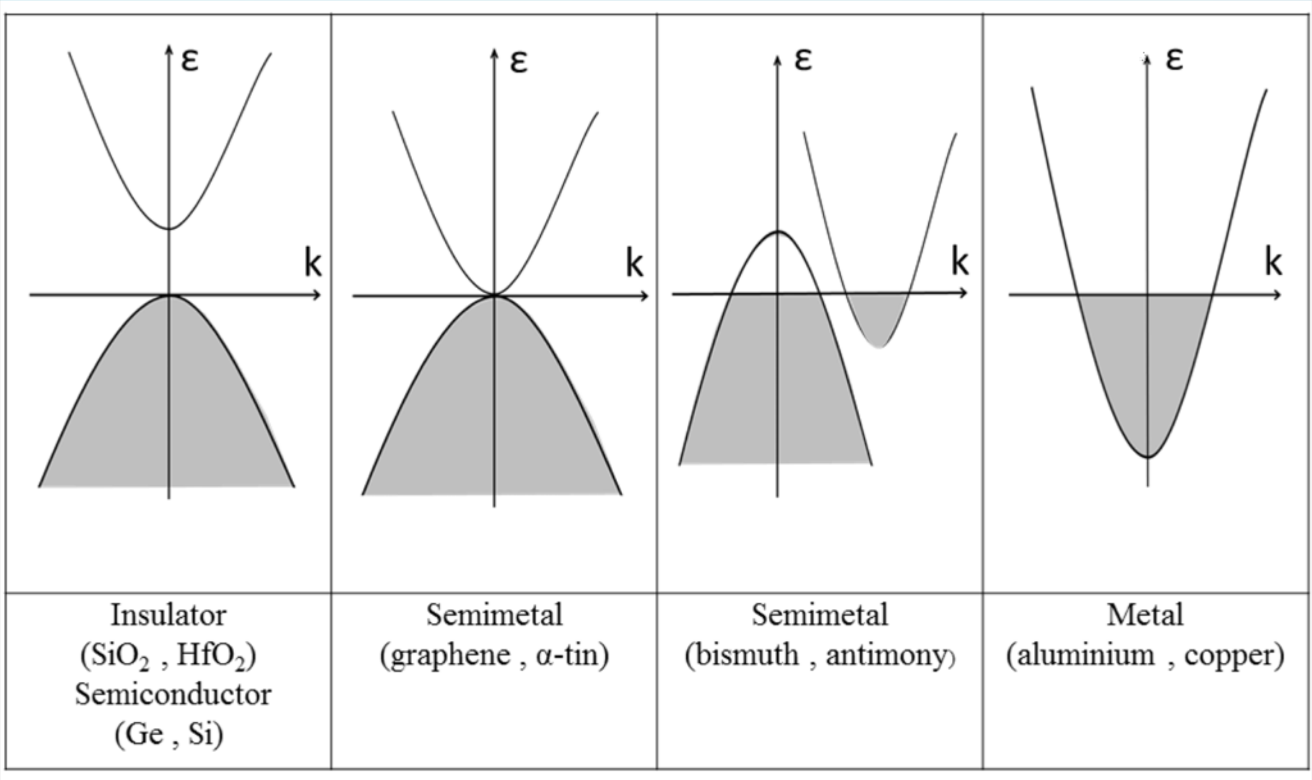
Each dot is a single silicon atom



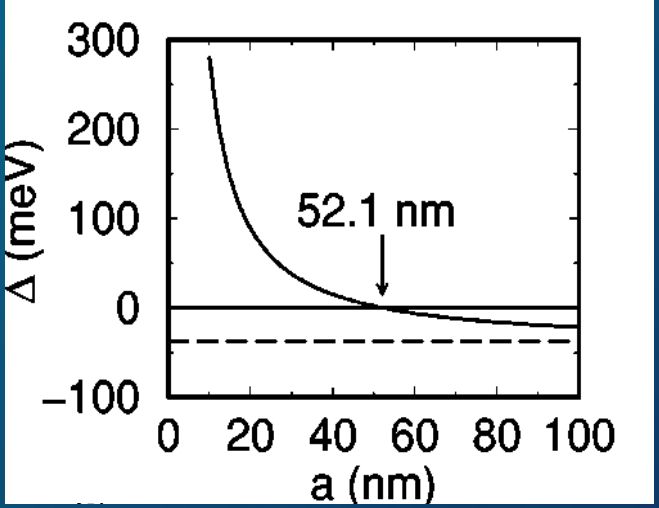
Billions of these tiny **switches** are required to make one **memory** chip or one **computer** chip that are in your **smart phones, tablets, laptops, ….**

Migita, Morita, Masahara, Ota, AIST (Japan), International Electron Devices Meeting 2012

Quantum alchemy:
semimetal to semiconductor transition



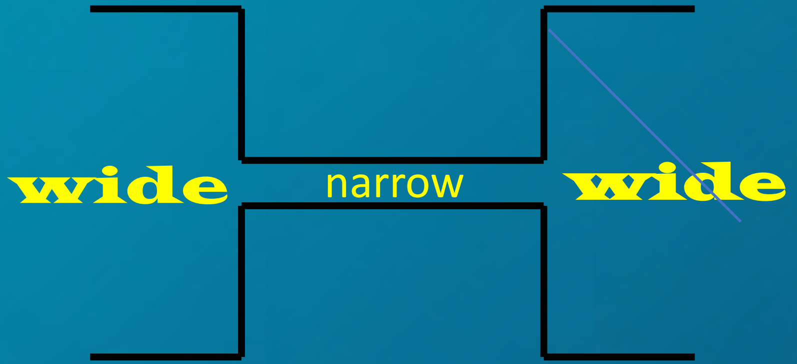
J.-P. Colinge & J.C. Greer, Nanowire Transistors: Cambridge Press, 2016



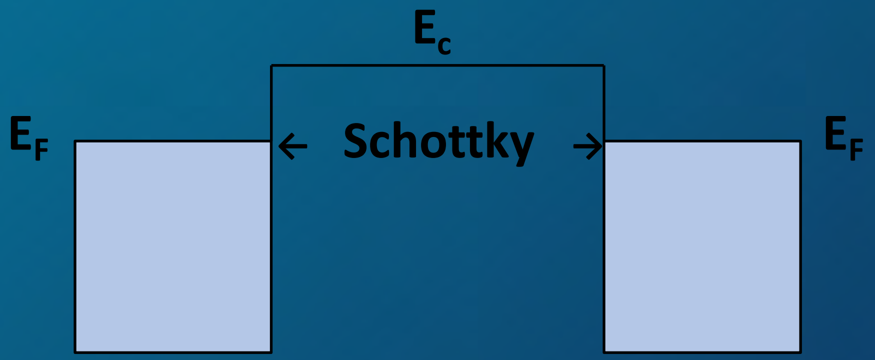
Theoretical description for bismuth
Sin, Zhang, Dresselhaus,
Appl. Phys. Letters 1999

Instead of fighting quantum effects, can we make them work for us?

Can we eliminate in doping electronics?



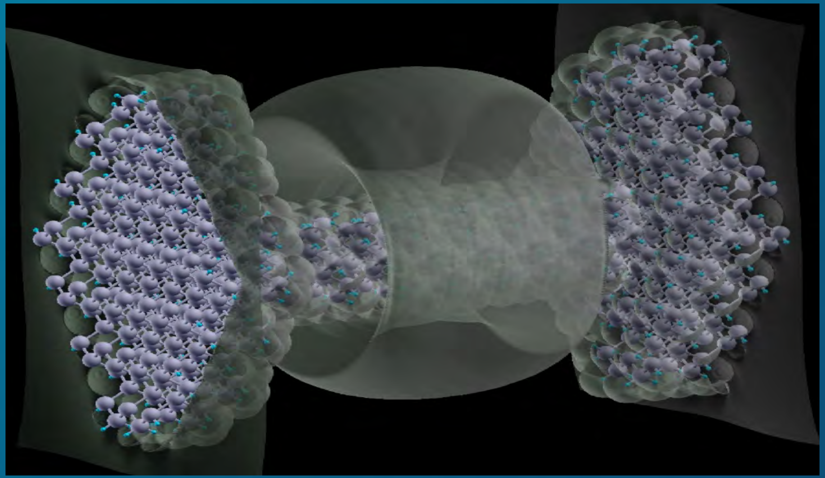
Geometry

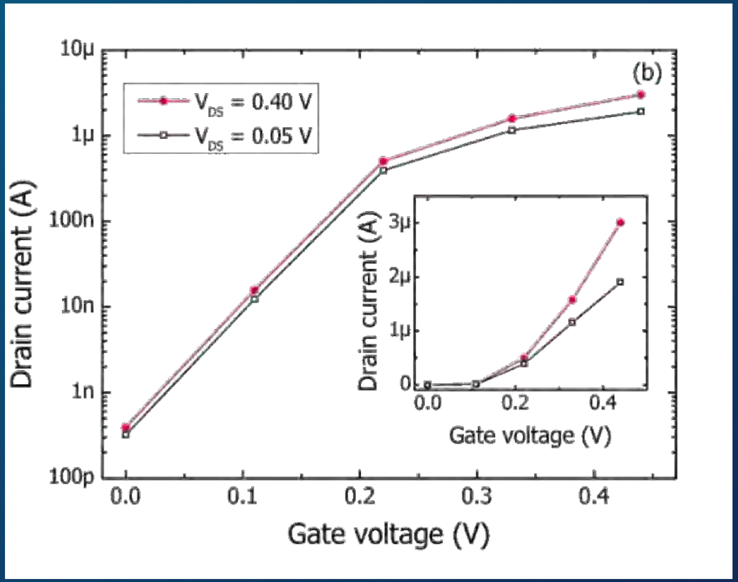


Band profile

α tin

Sn





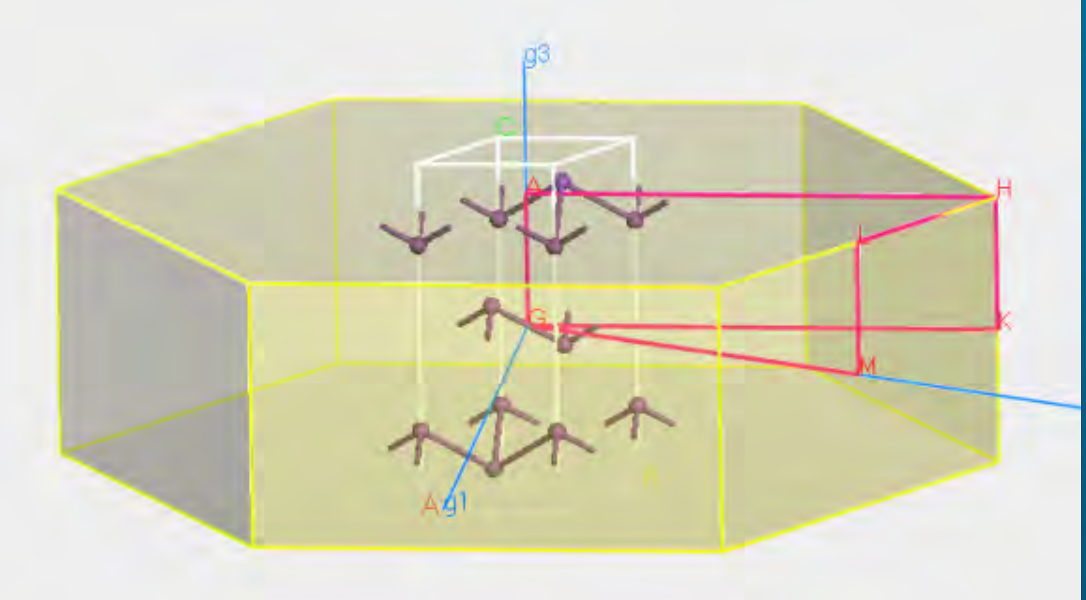
L. Ansari, G. Fagas, J.-P. Colinge, J. C. Greer, Nano Lett., 2012

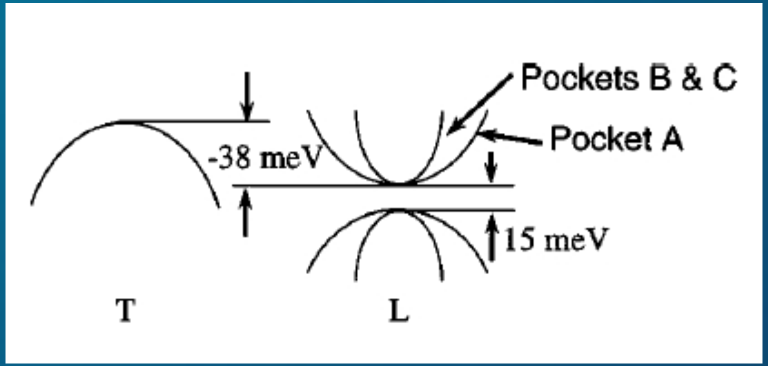
Good ON/OFF characteristics

SS: 73 mV/dec

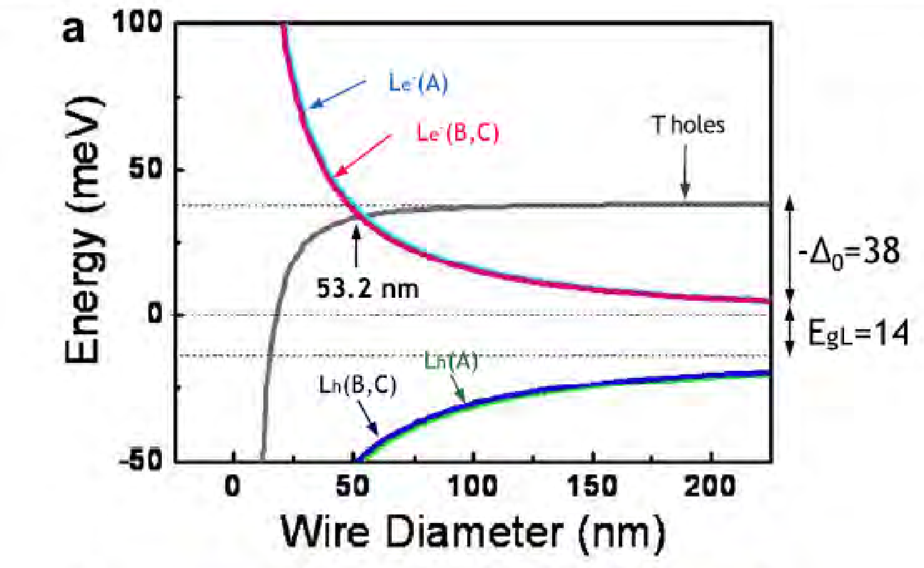
Another semimetal: bismuth (Bi)

Bulk





Semimetal-to-semiconductor transition at diameter between 50 and 70 nm



Z. Zhang, *et al*, PRB, 2000

Electrical characterisation of Bi thin films

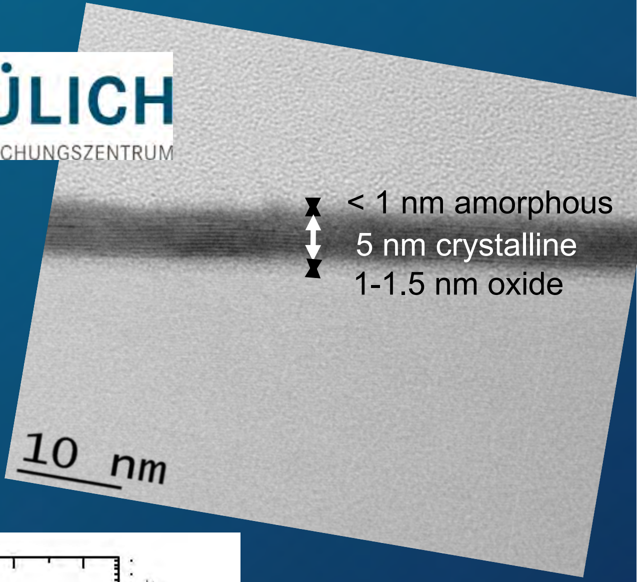
Hall measurement results:

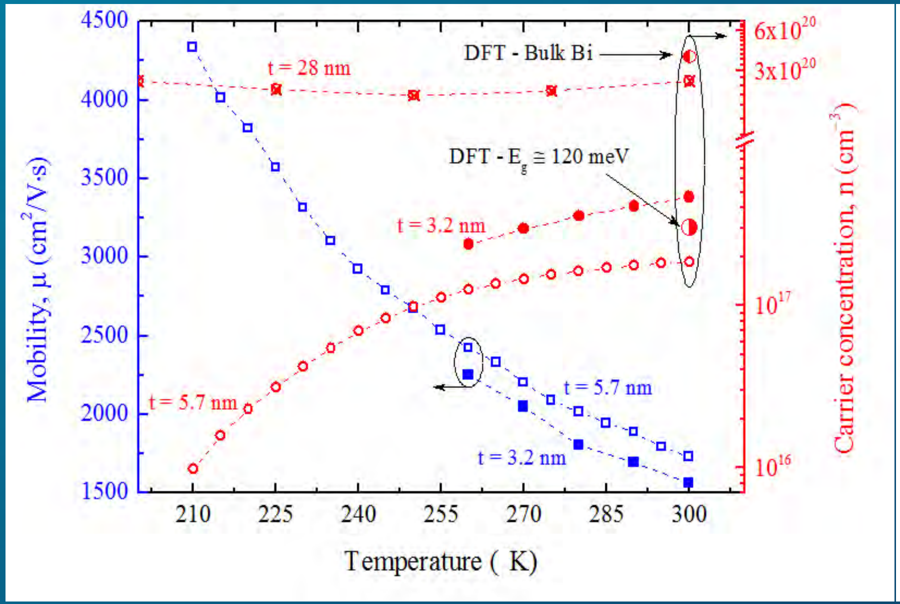
High mobility (~3 time higher than Si at 300 K)

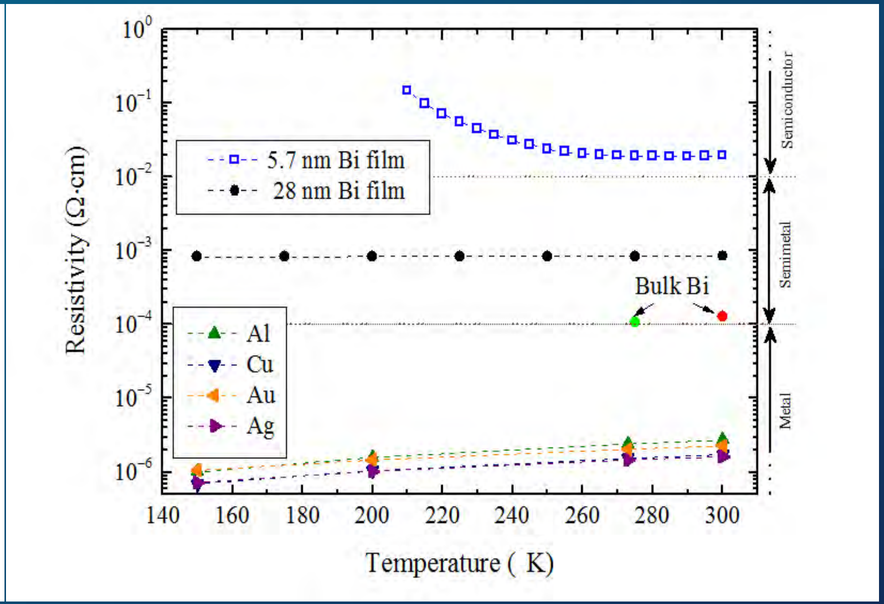
Reduction of carrier concentration with temperature

=> ΔE ≈ 117 meV

Resistivity of crystalline 5.7 nm Bi film is well within the semiconducting range and displays increased resistivity with lowering temperature.

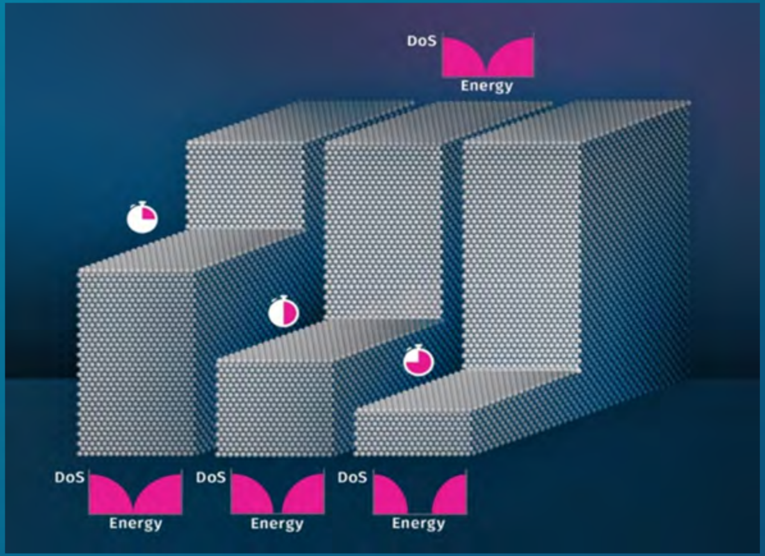


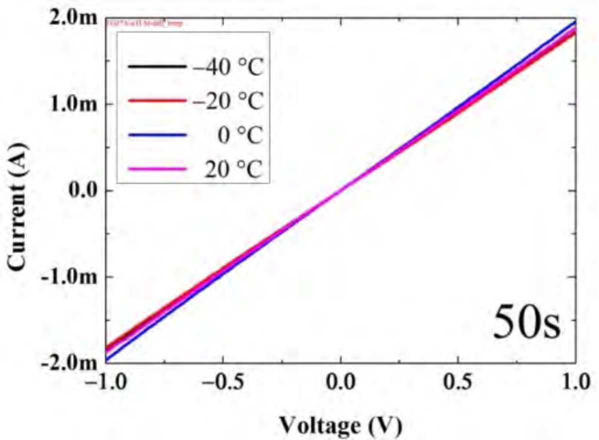


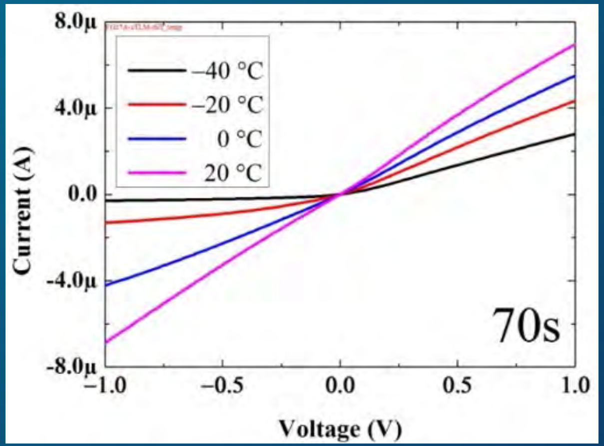


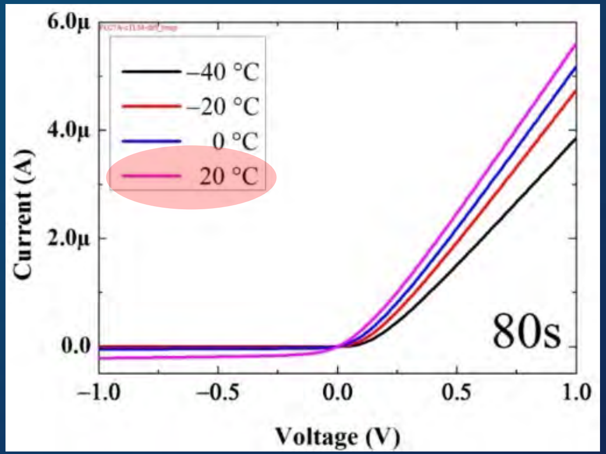
F. Gity, L. Ansari, M. Lanius, P. Schüffelgen, G. Mussler, D. Grützmacher, J. C. Greer, APL ,2017

Making an old device in a new way: the diode



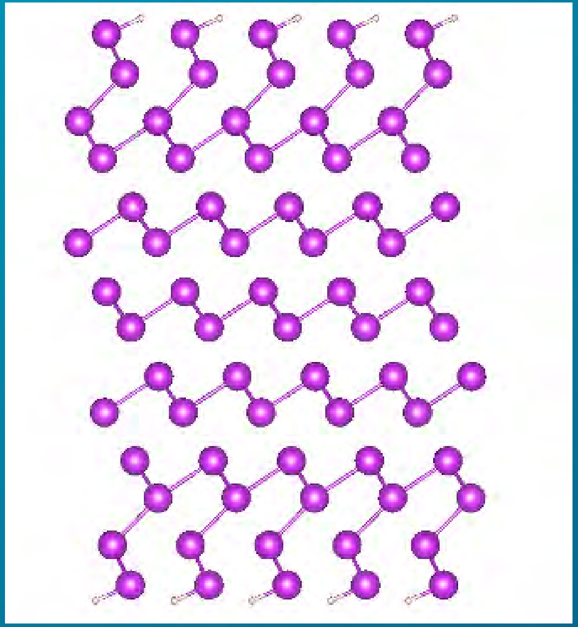




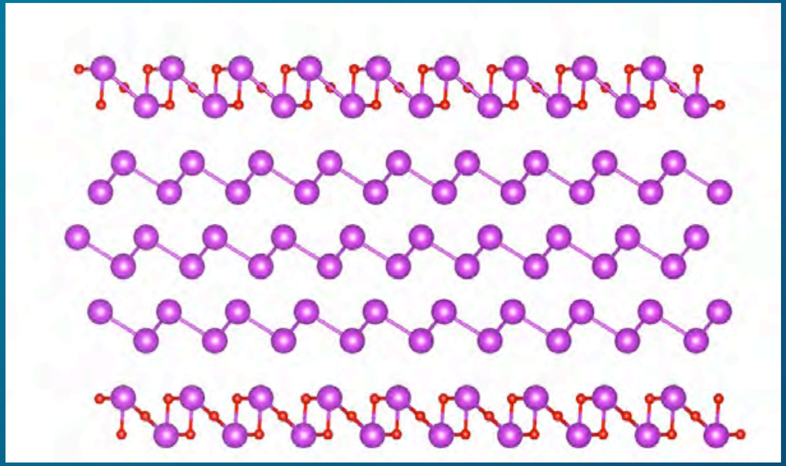


F. Gity, L. Ansari, M. Lanius, P. Schüffelgen, G. Mussler, D. Grützmacher, J. Greer APL, 2017

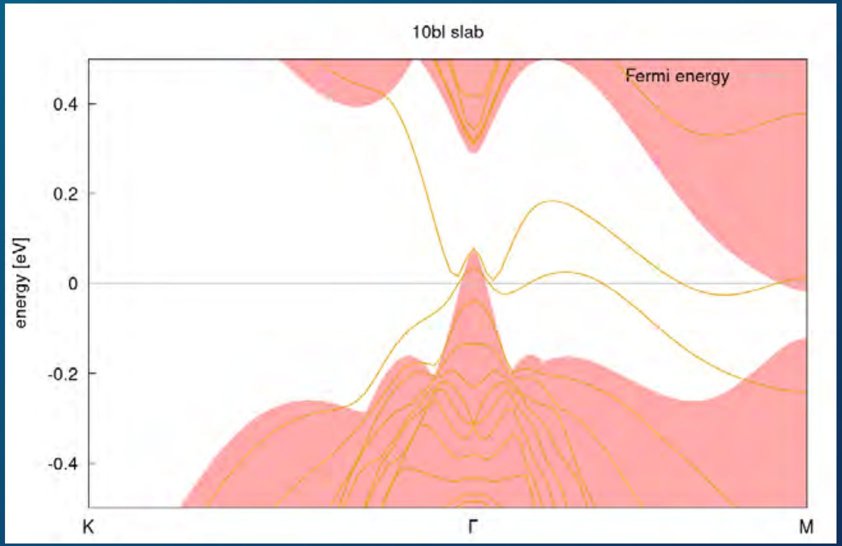
Puzzling electronic behaviour of Bi thin films



Surface reorganisation



Weakly interacting oxide



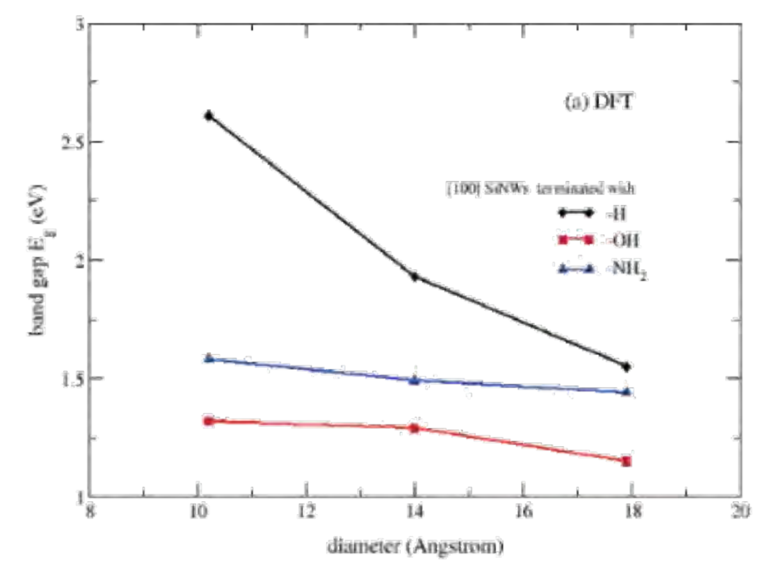
Robust spin split surface states

König, Fahy, Greer, PRM, 2019

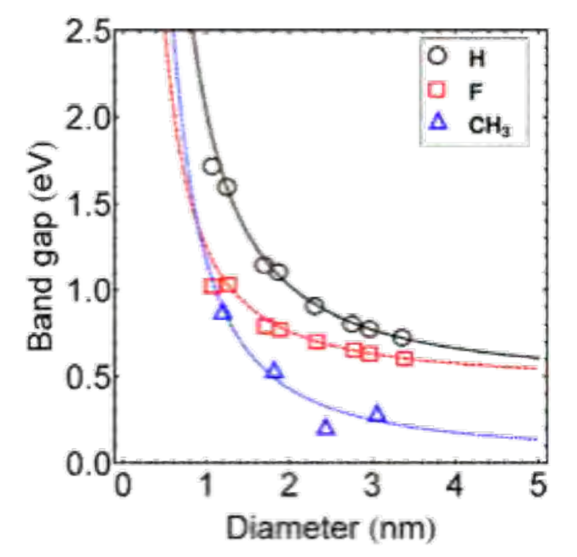
Surface functionalization of Si nanowires

Passivating surface bonds of sub-10-nm Si nanowires allows modulation of electronic properties such as work function and band gap

Density functional theory (DFT) calculations predict variations in band gap energies of the order of electron volts (eV)



Nolan *et al.*, Nano Lett., 2007



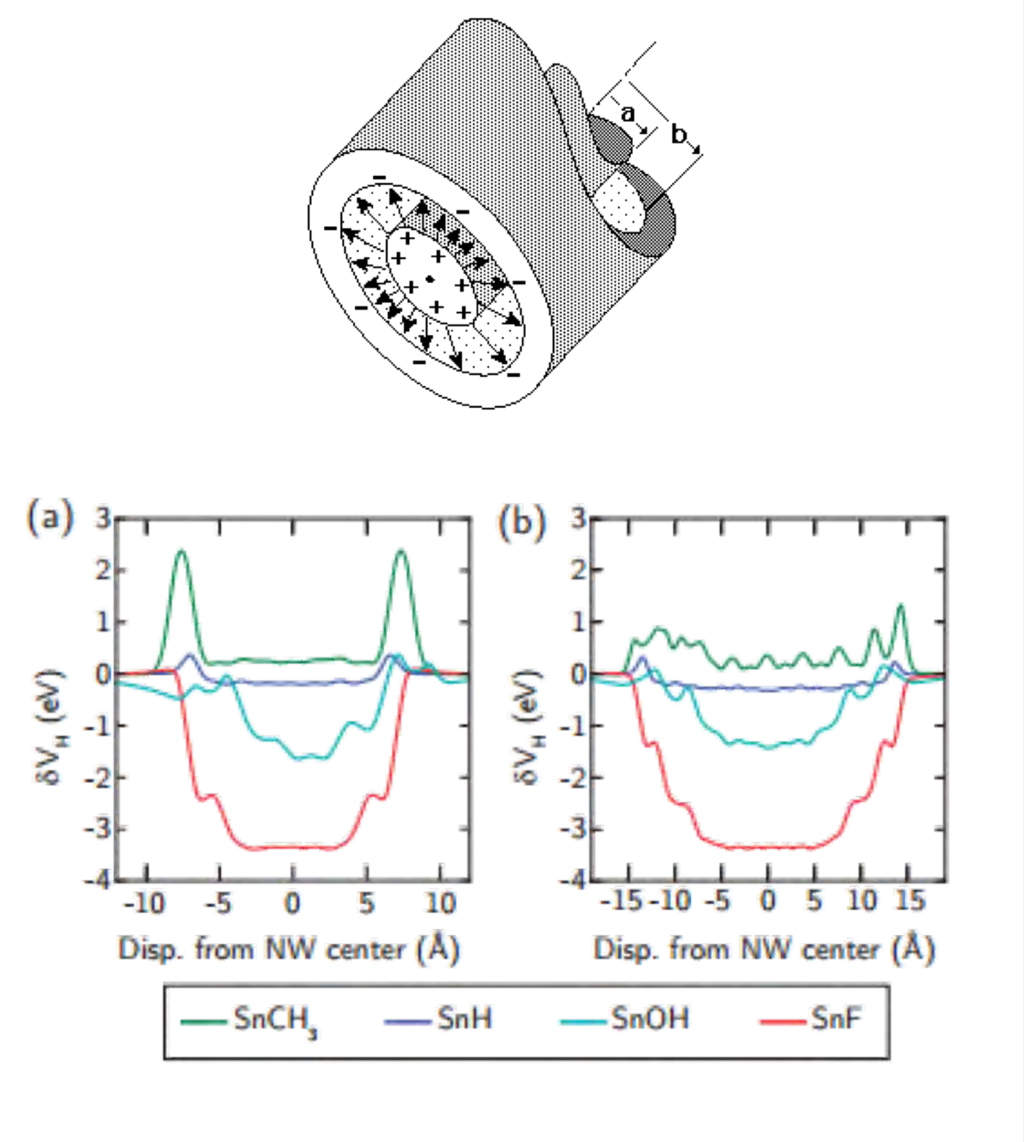
Zhuo and Chou, JPCM, 2013

Surface dipoles modulate Sn NW electrostatics

Potential well depths dependant on the magnitude of the surface dipoles

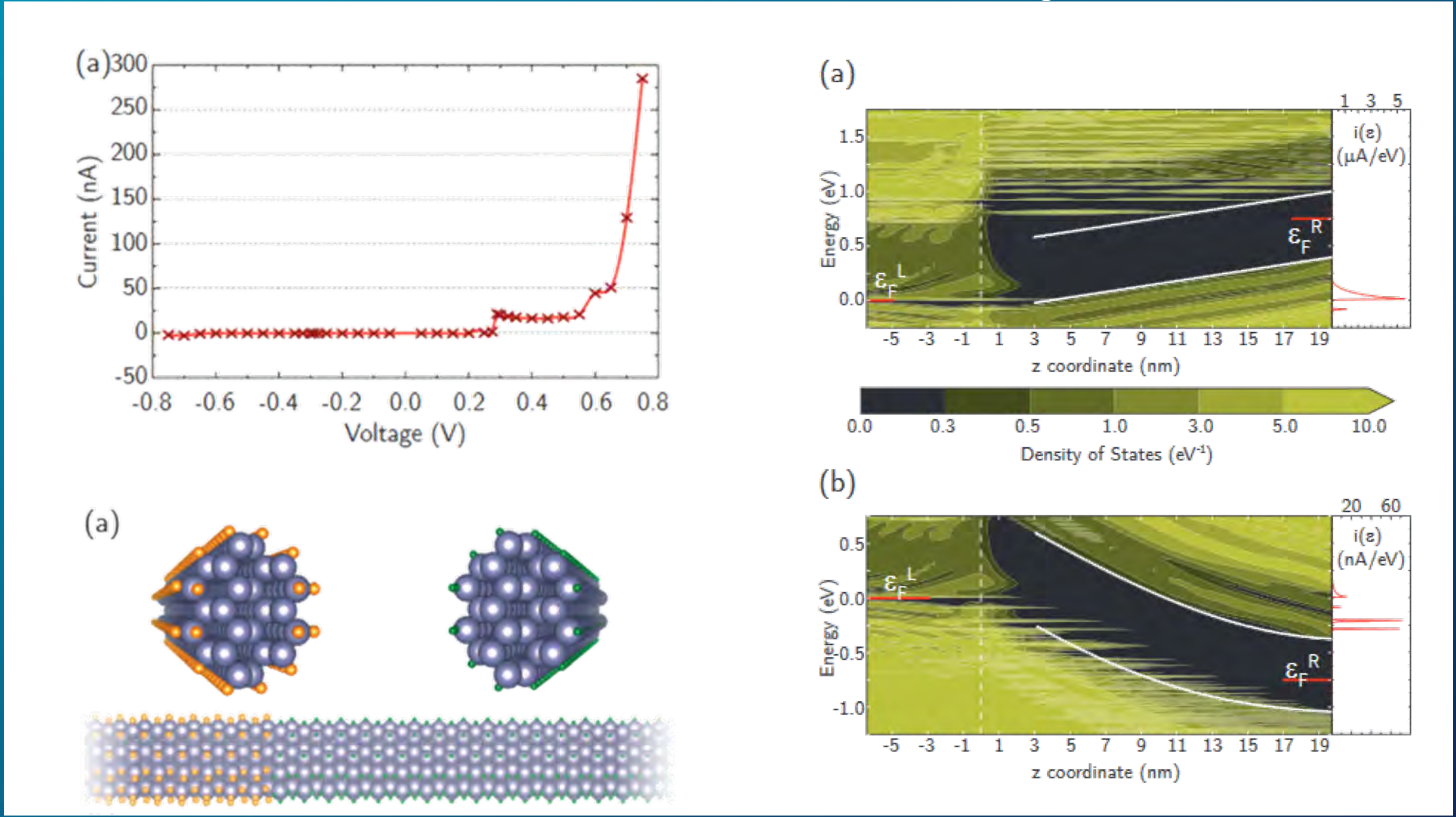
$$\Delta\varphi = \frac{\rho_S}{2\pi\varepsilon_0}\ln\frac{b}{a}$$

Potential well depths correlate to passivant electronegativity



A. Sanchez-Soares, C. O'Donnell and J. C. Greer, PRB, 2016

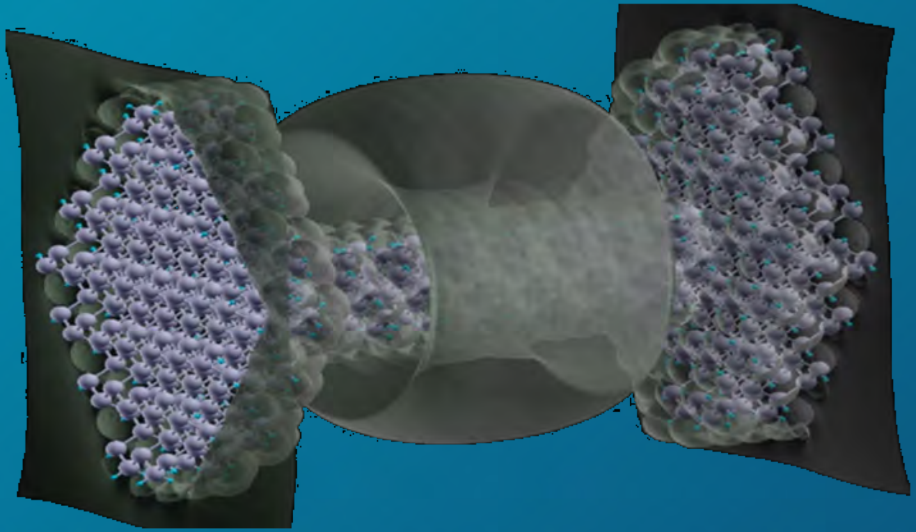
Semimetal-semiconductor junction by surface chemistry



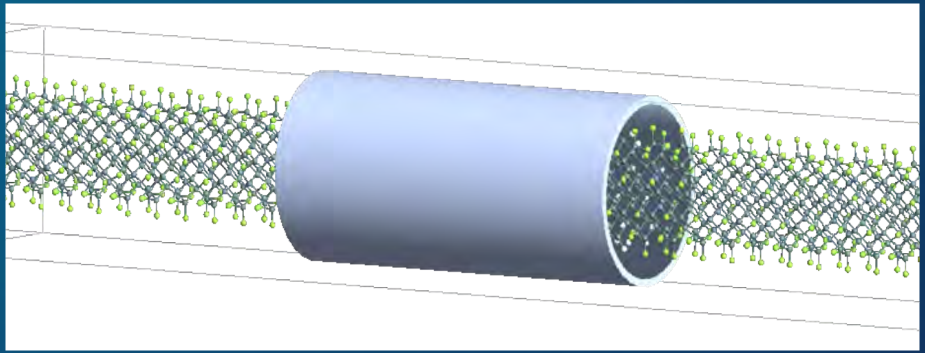
A. Sanchez-Soares and J. C. Greer, Nano Lett, 2016

Semimetal-semiconductor junction by surface chemistry

By geometry



By surface chemistry



… without substitutional doping

Summary

The formation of *pn* junctions or introducing dopant atoms is challenging due to small length scales and the dopant fluctuation problem (too few dopant atoms)

The semimetal-to-semiconductor transition occurs at small length scales due to quantum confinement

The large surface-to-volume ratio in nanostructures allows for surface chemistry to modify bandgaps

Quantum confinement and surface chemistry allow for design of conventional transistors by unconventional means

How can Bi thin films be both semiconducting and metallic?

Acknowledgments

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Vielen Dank
谢谢