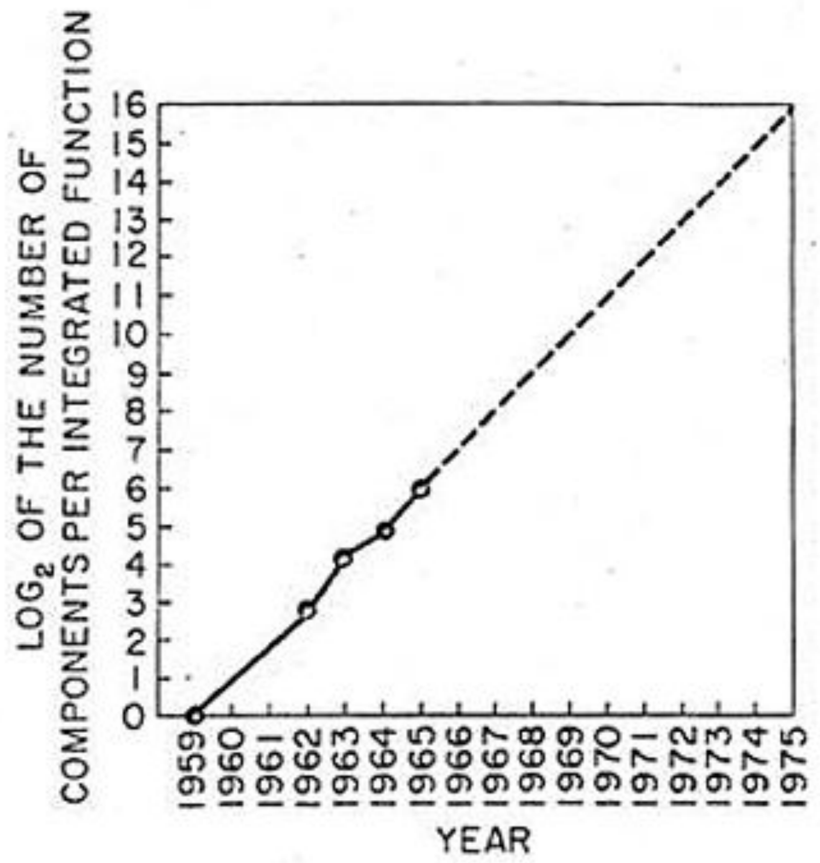
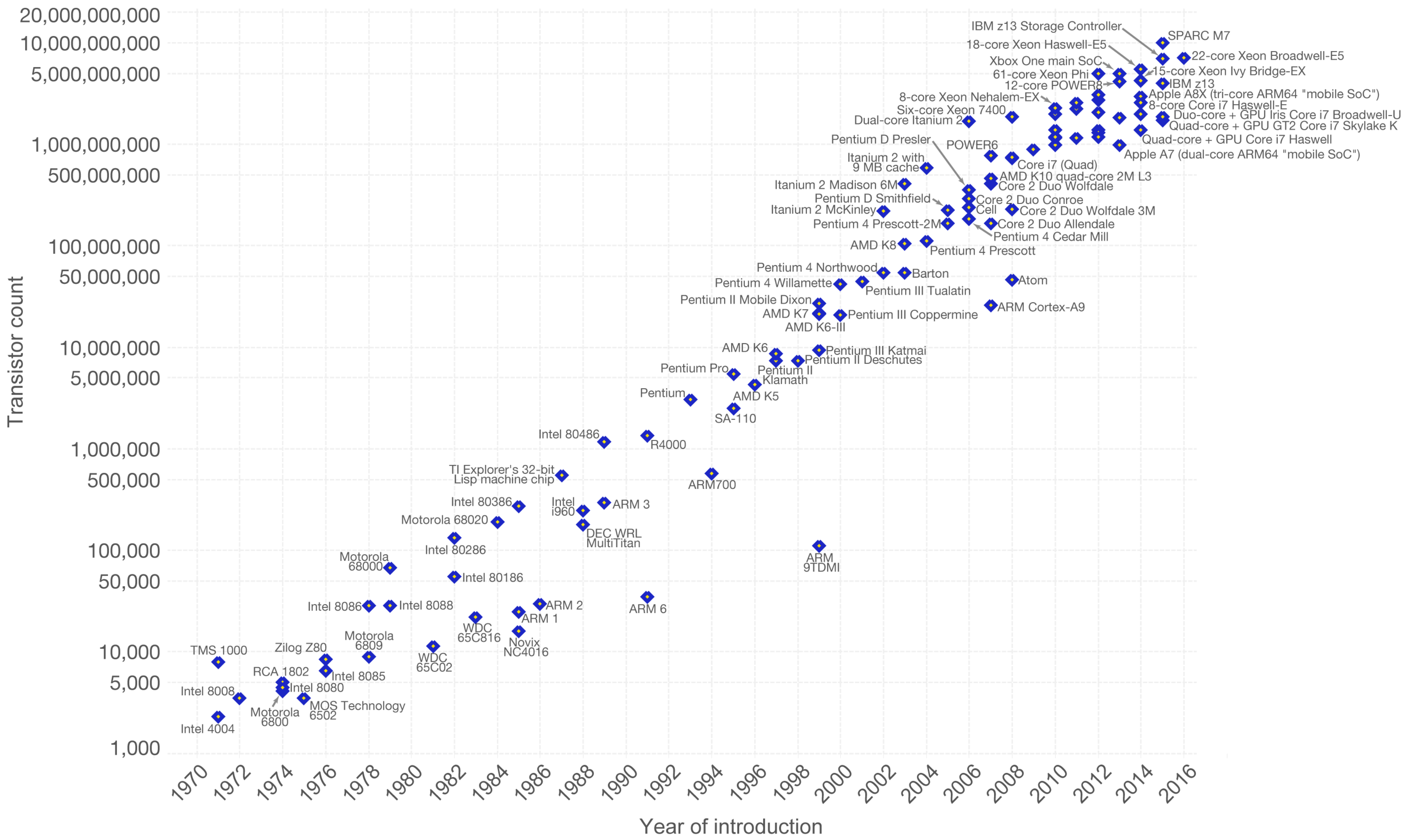
Electron Transport and Nanodevices with Low-Dimensional Materials

Luis E. Hueso

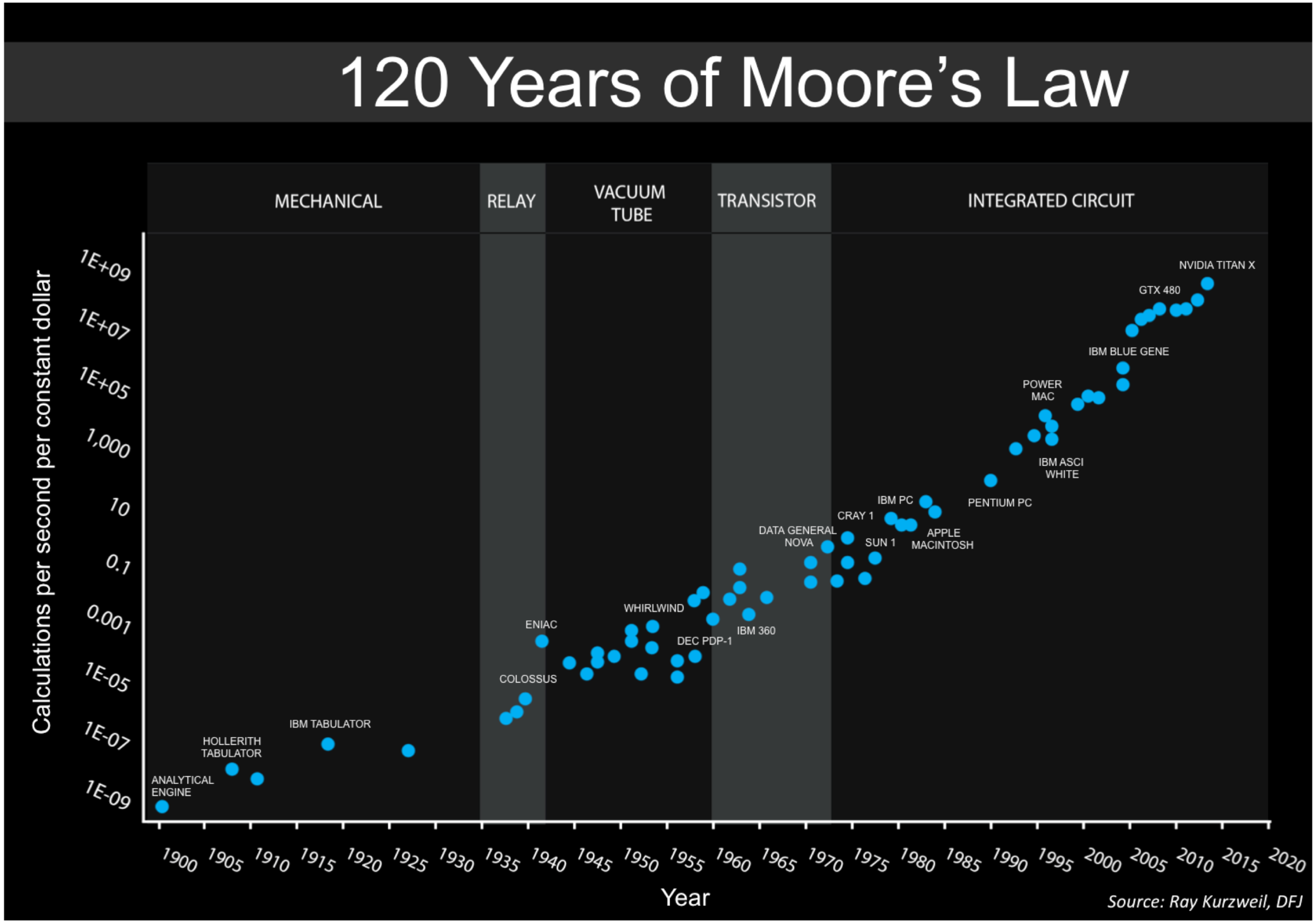
Evolution in the Electronics Industry



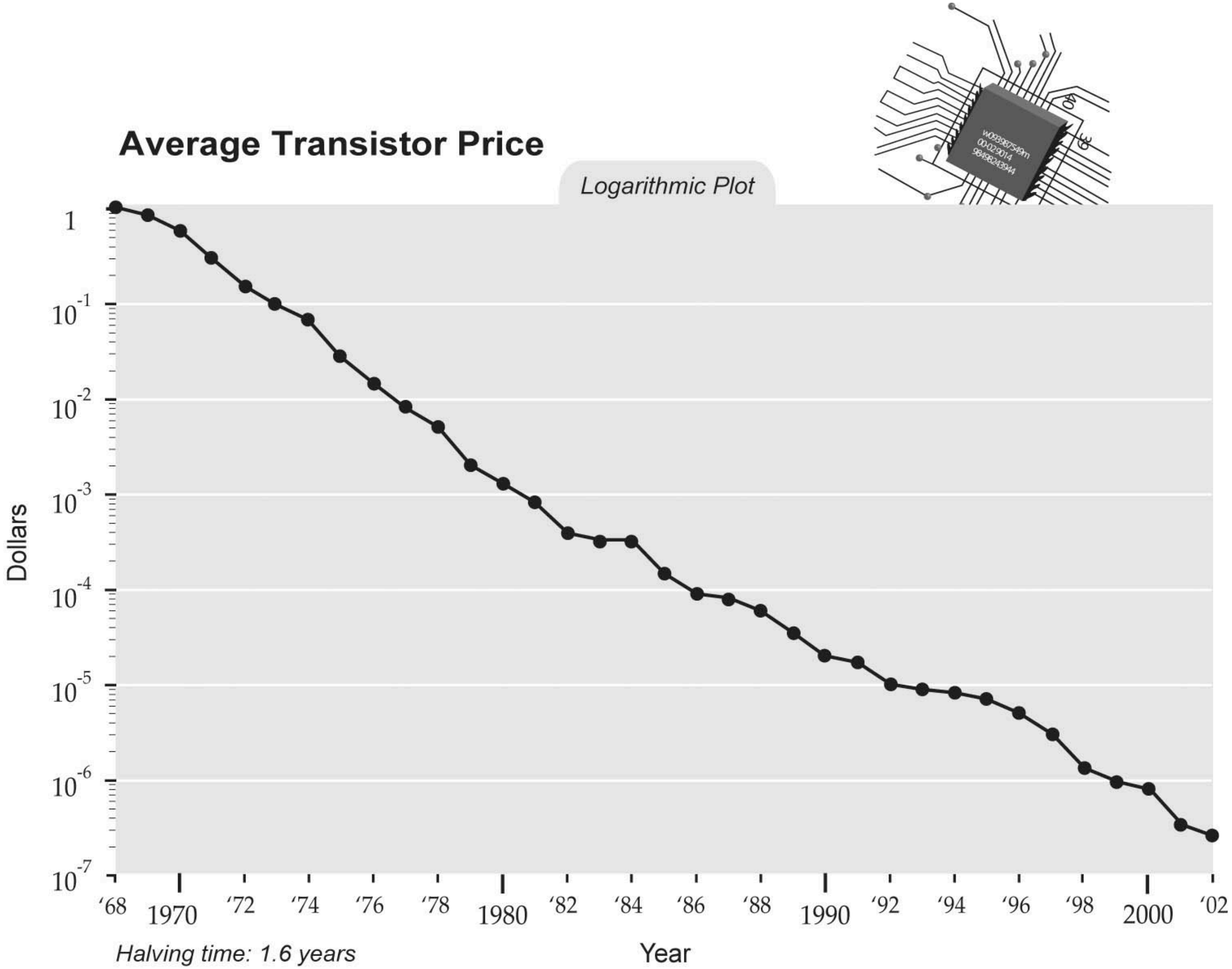
Evolution in the Electronics Industry



Evolution in the Electronics Industry

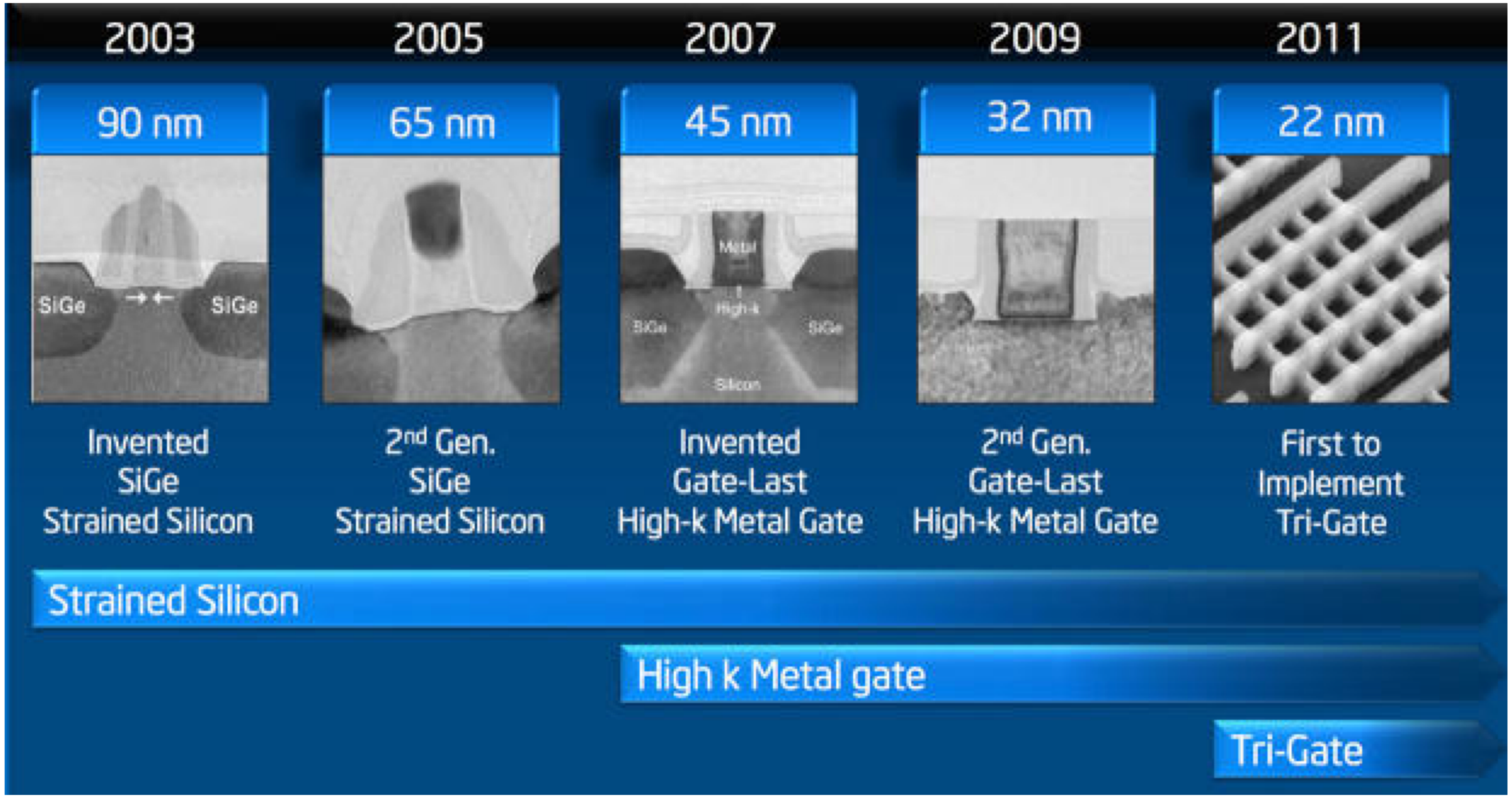


Evolution in the Electronics Industry



Evolution in the Electronics Industry

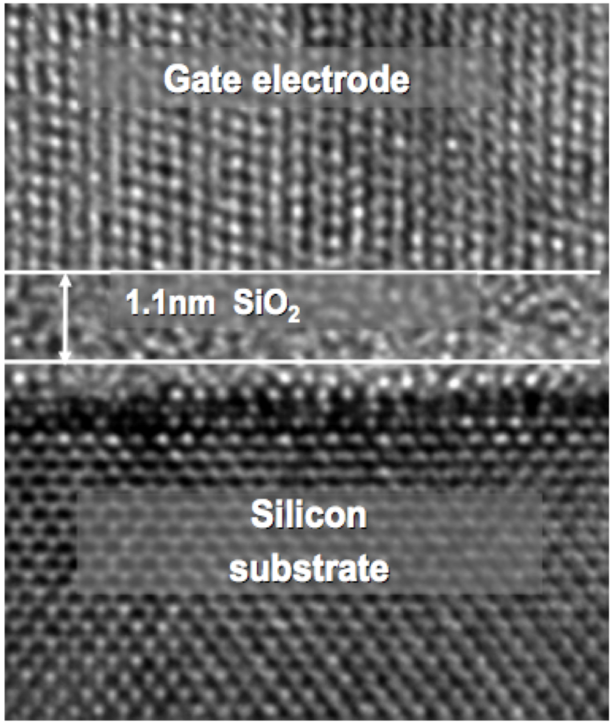
Continuous scientific achievements for the electronics industry

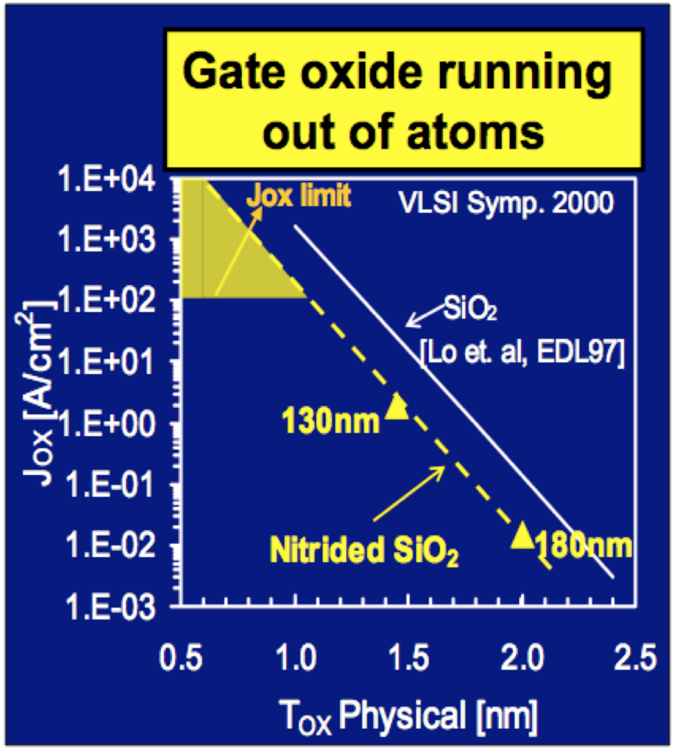


Evolution and materials science

Year 2003: the gate dielectric oxide cannot get thinner

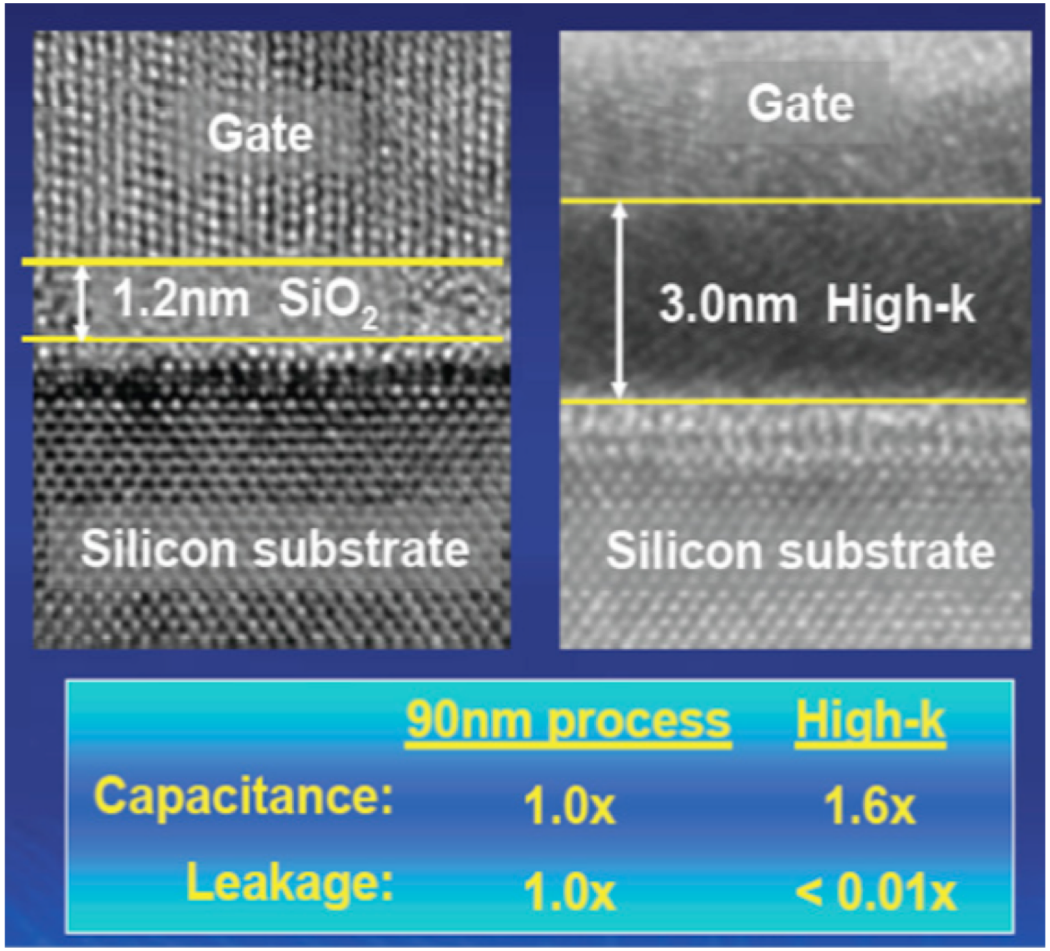
Tunnel current not sustainable



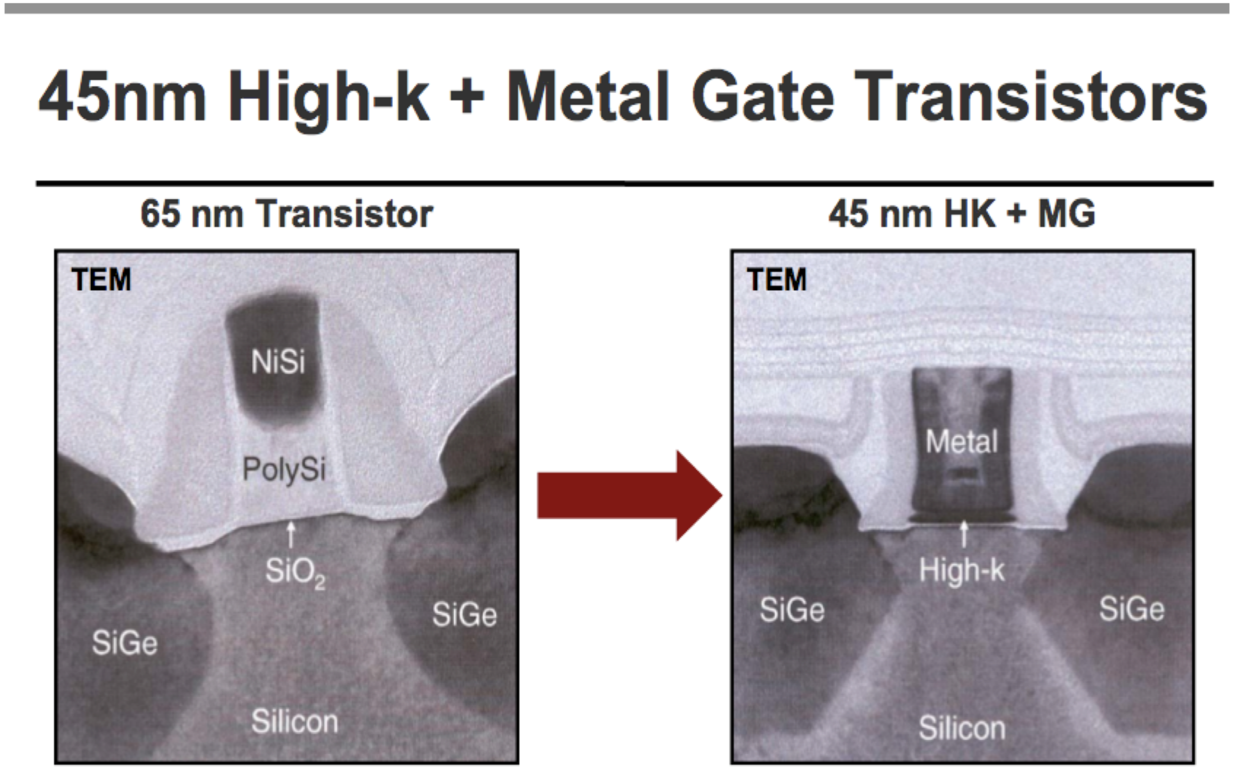


Evolution and materials science

Development in materials science

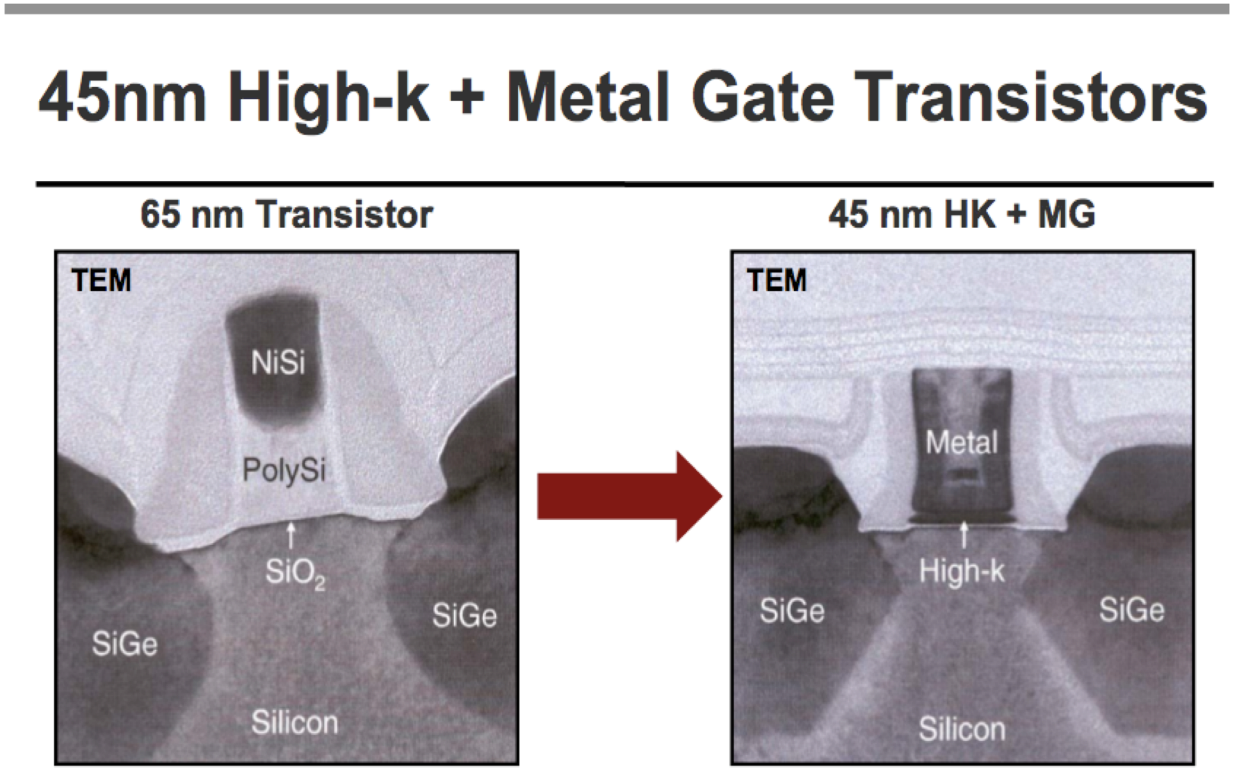


Evolution and materials science



New generation of devices based on a new material: HfO_2

Evolution and materials science

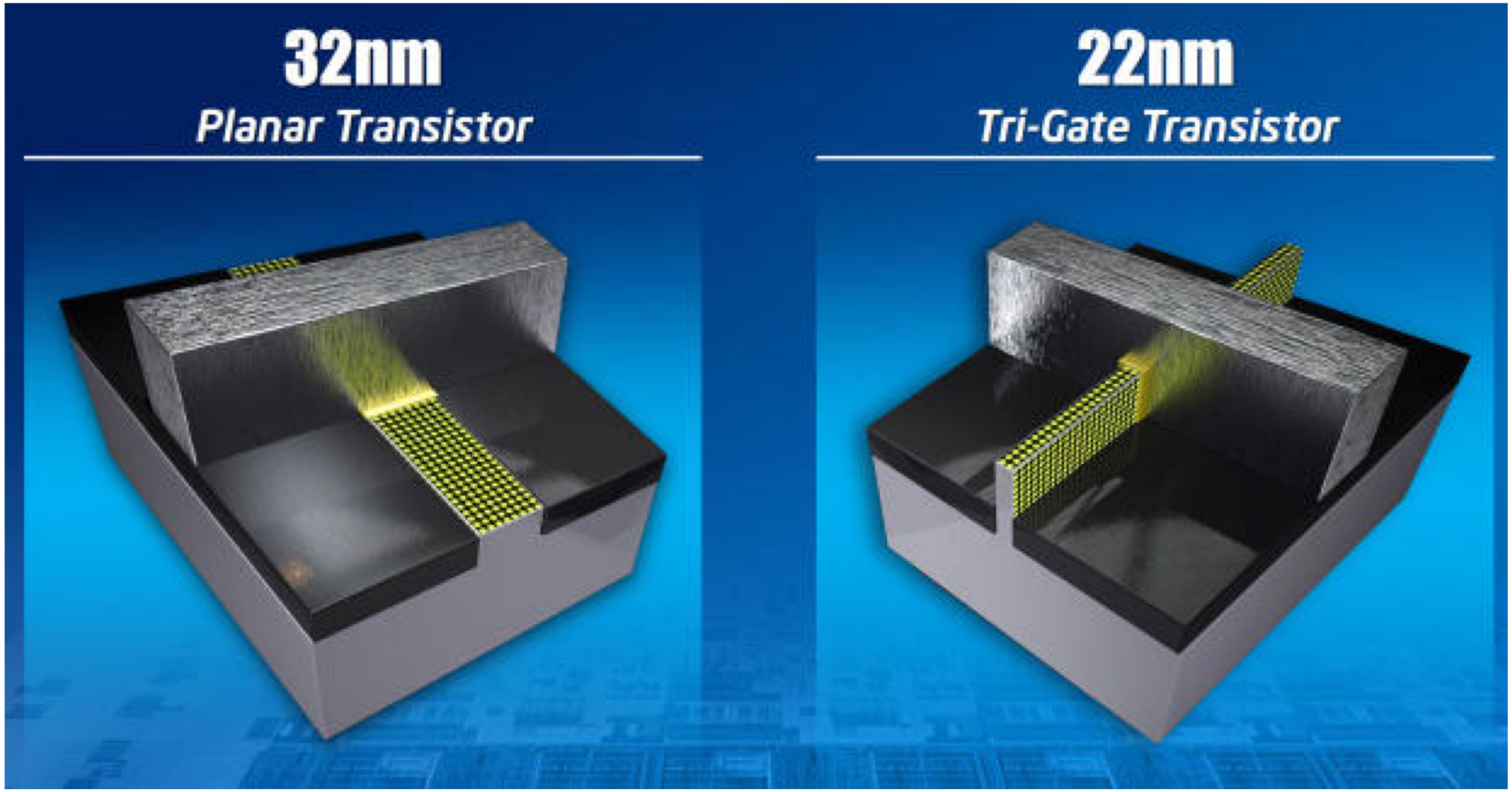


30% less required power

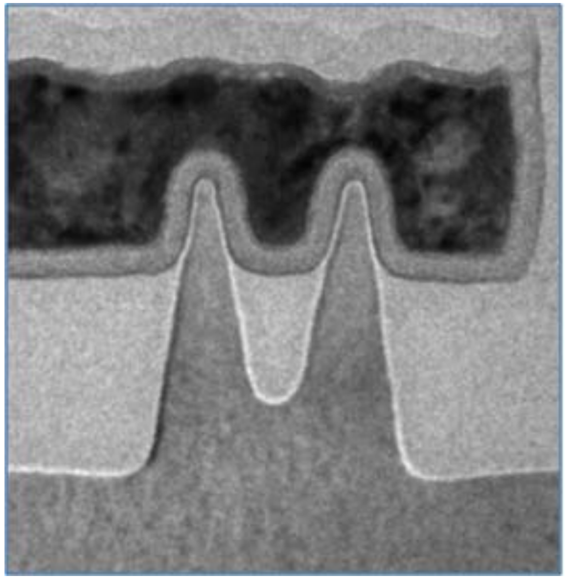
30% larger output current

Evolution and electronic engineering

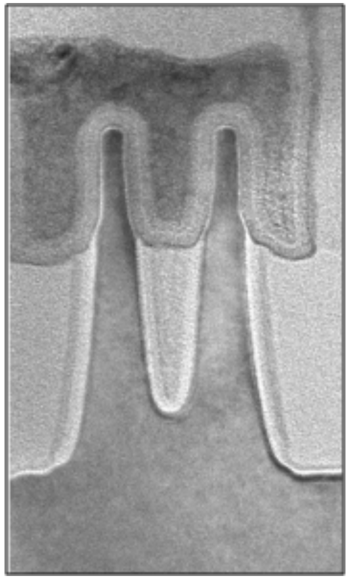
Year 2010: the gate has not enough efficiency



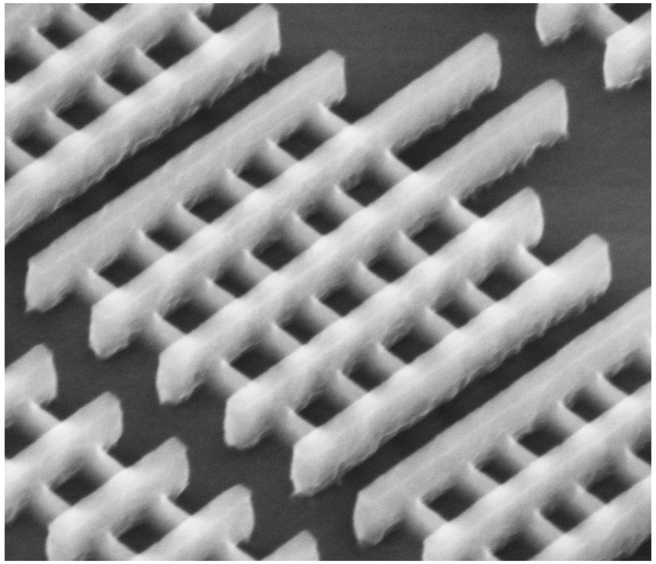
Evolution and electronic engineering



22 nm Process



14 nm Process

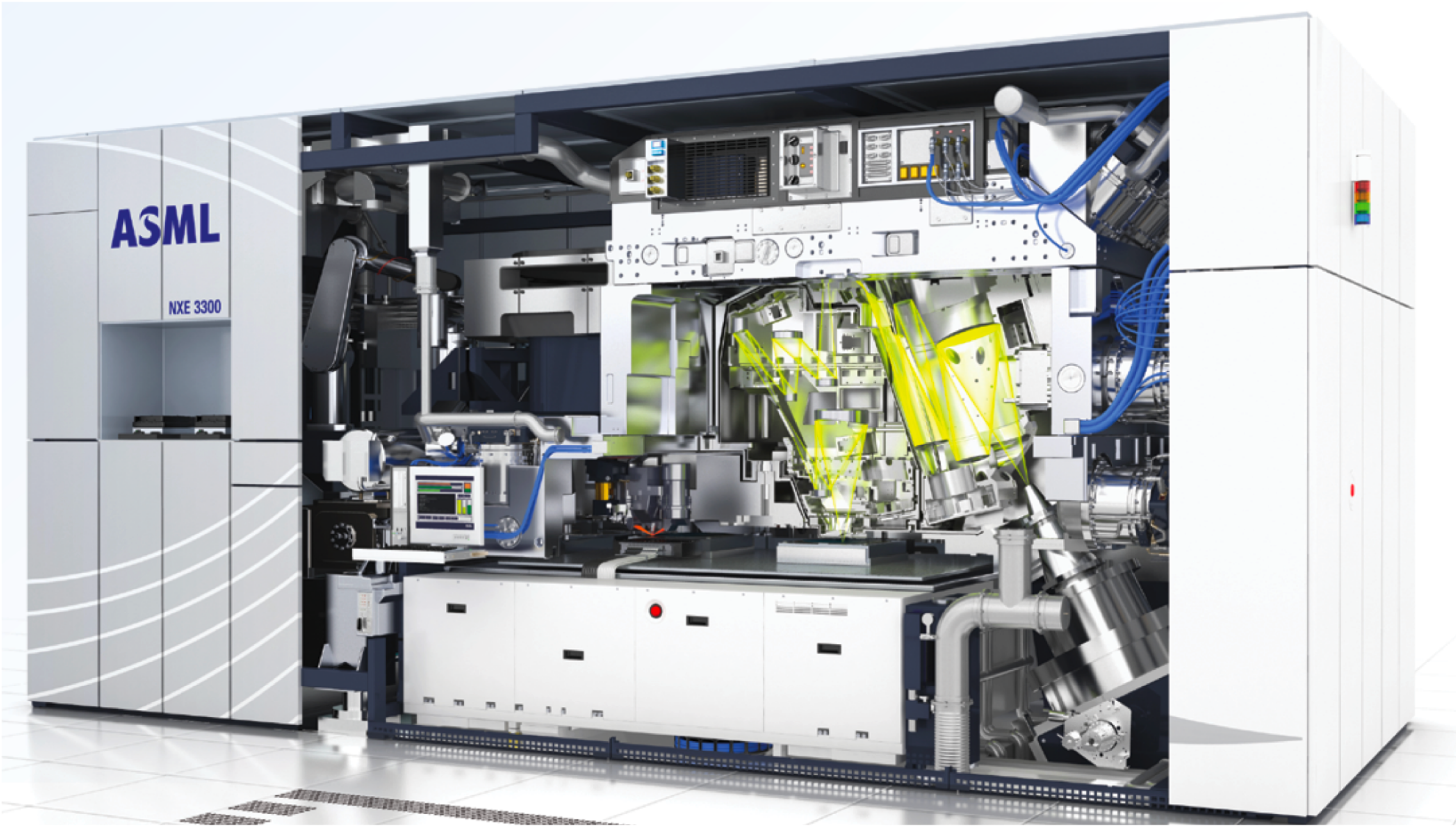


50% less required power

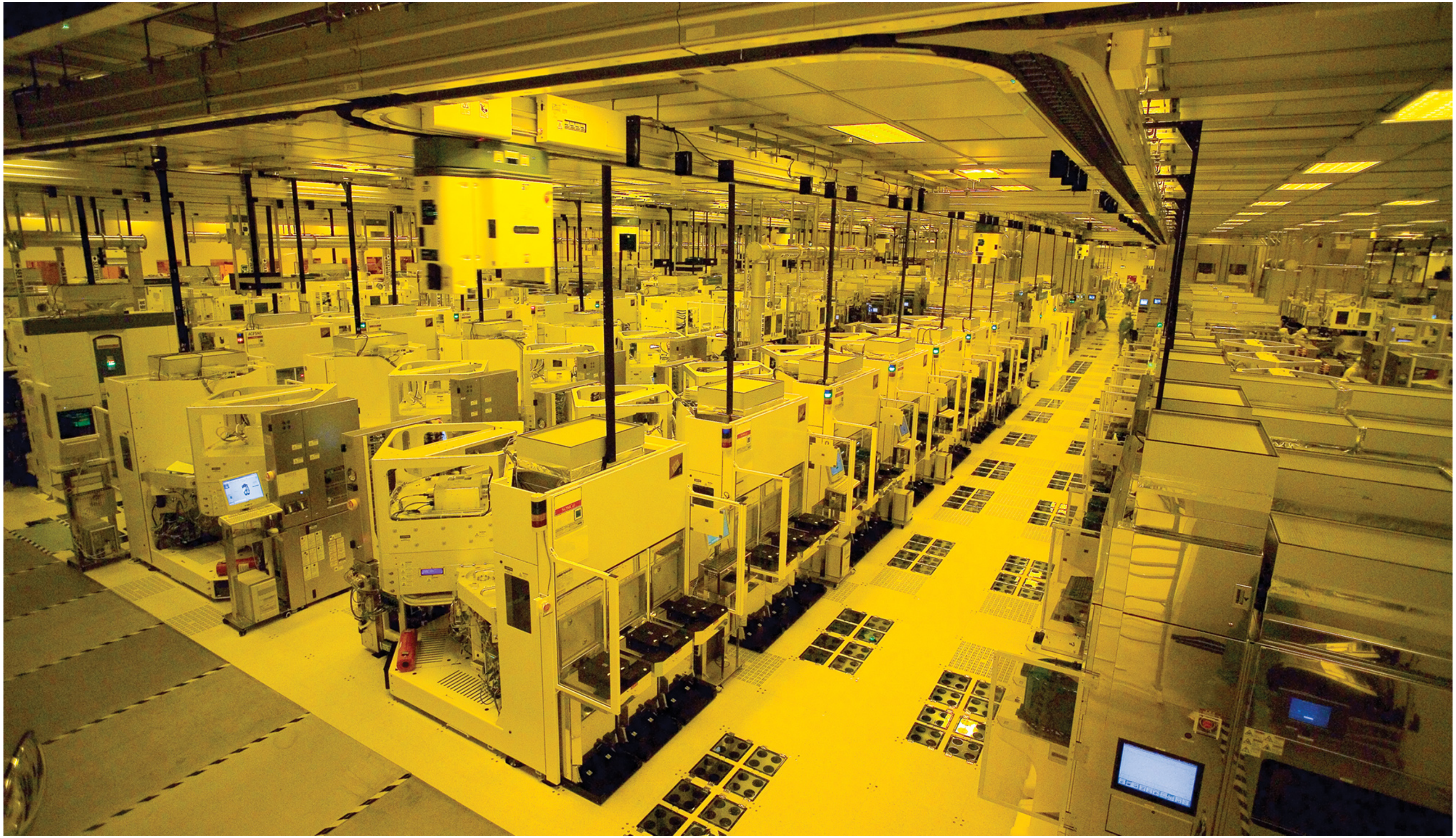
25% better performance

Evolution and fabrication developmetns

From 2001 developing EUV lithography. Finally into the market



Evolution in the Electronics Industry. Issues



Evolution in the Electronics Industry. Issues

130nm	90nm	65nm/55nm	45/40nm	32/28nm	22/20nm
Altis Semiconductor					
Dongbu Hitek	Dongbu Hitek				
Freescale	Freescale				
Fujitsu	Fujitsu				
Globalfoundries	Globalfoundries	Freescale			
Grace Semiconductor	Grace Semiconductor	Fujitsu			
IBM	IBM	Globalfoundries			
Infineon	Infineon	IBM			
Intel	Intel	Infineon	Fujitsu		
Panasonic	Panasonic	Intel	Panasonic		
Renesas (NEC)	Renesas (NEC)	Panasonic	Globalfoundries		
Samsung	Samsung	Renesas (NEC)	IBM		
Seiko Epson	Seiko Epson	Samsung	Intel		
SMIC	SMIC	SMIC	Renesas (NEC)	Globalfoundries	
Sony	Sony	Sony	Samsung	Intel	
ST Microelectronics	ST Microelectronics	ST Microelectronics	SMIC	Panasonic	Globalfoundries
Texas Instruments	Texas Instruments	Texas Instruments	ST Microelectronics	Samsung	Intel
Toshiba	Toshiba	Toshiba	Toshiba	ST Microelectronics	Samsung
TSMC	TSMC	TSMC	TSMC	TSMC	ST Microelectronics
UMC	UMC	UMC	UMC	UMC	TSMC

Partial summary

Evolution unseen in any other industrial sector in the whole human history

Potential issues have been solved by intensive research

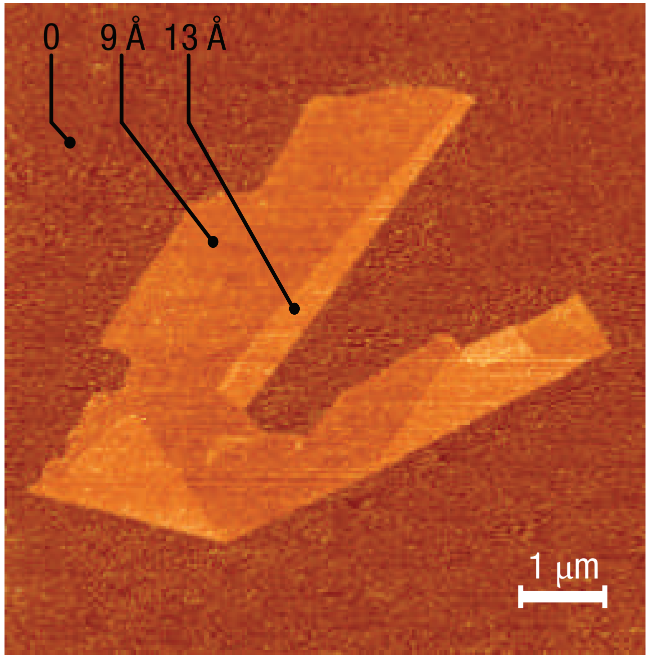
New materials can offer new solutions and new opportunities

New materials lead to new physics

The rise of graphene

First images of graphene as monolayer

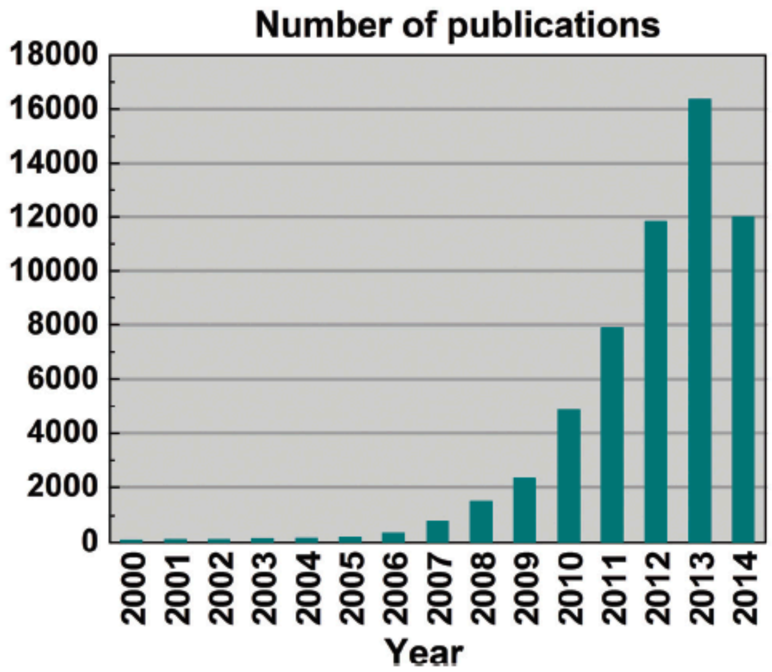
Serendipity and research go together



K.S. Novoselov et al., Science 306, 666 (2004)

The rise of graphene

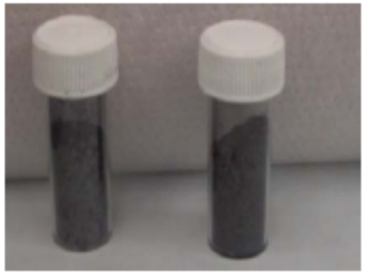
The most important scientific topic in the last few decades (not only in CM)

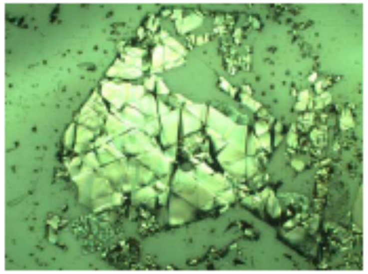


A. Ferrari et al., Nanoscale 7, 4598 (2015)

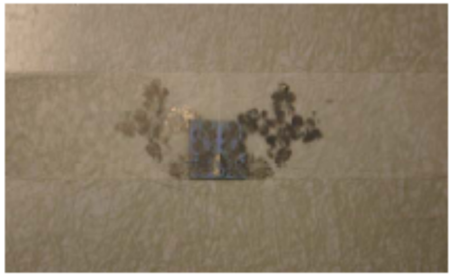
The rise of graphene

Full fabrication process. From low to high-tech

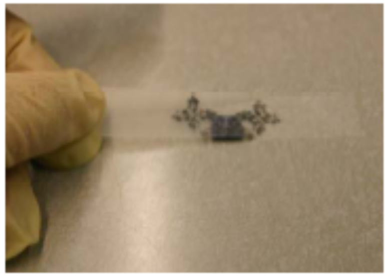

Graphite Flakes (Kish, Toshiba Ceramics)


Graphite Flake


Peeling a Graphite Flake


Cleaving to a SiO_2/Si waver

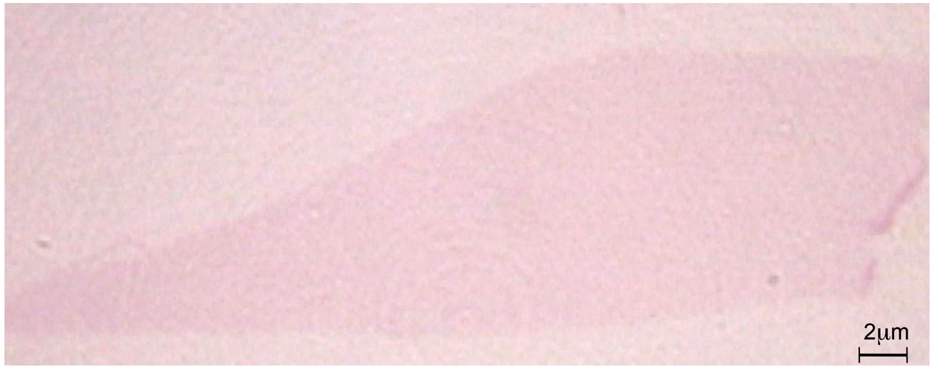

Gentle Rubbing with plastic Tweezers

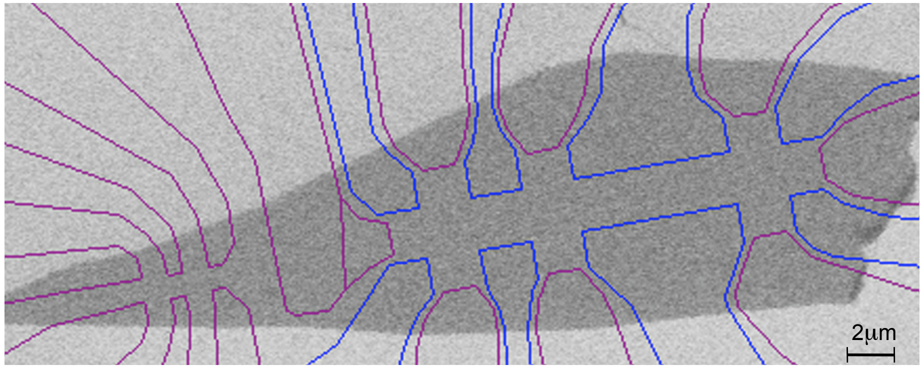

Removing the Scotch Tape

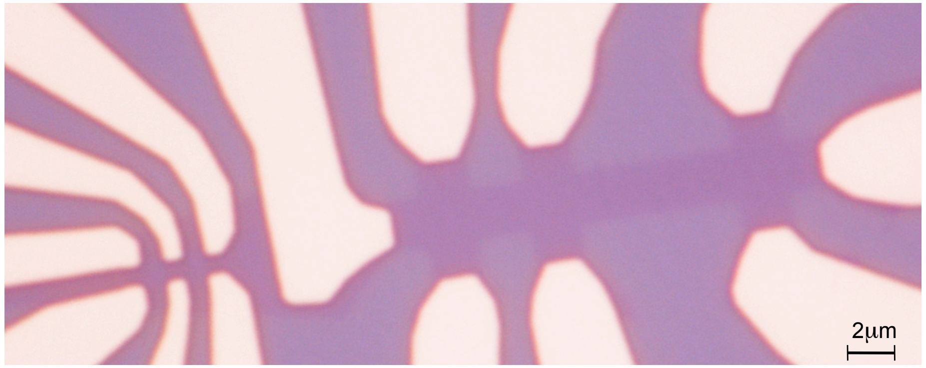
K.S. Novoselov et al., Science 306, 666 (2004)

The rise of graphene

Full fabrication process. From low to high-tech



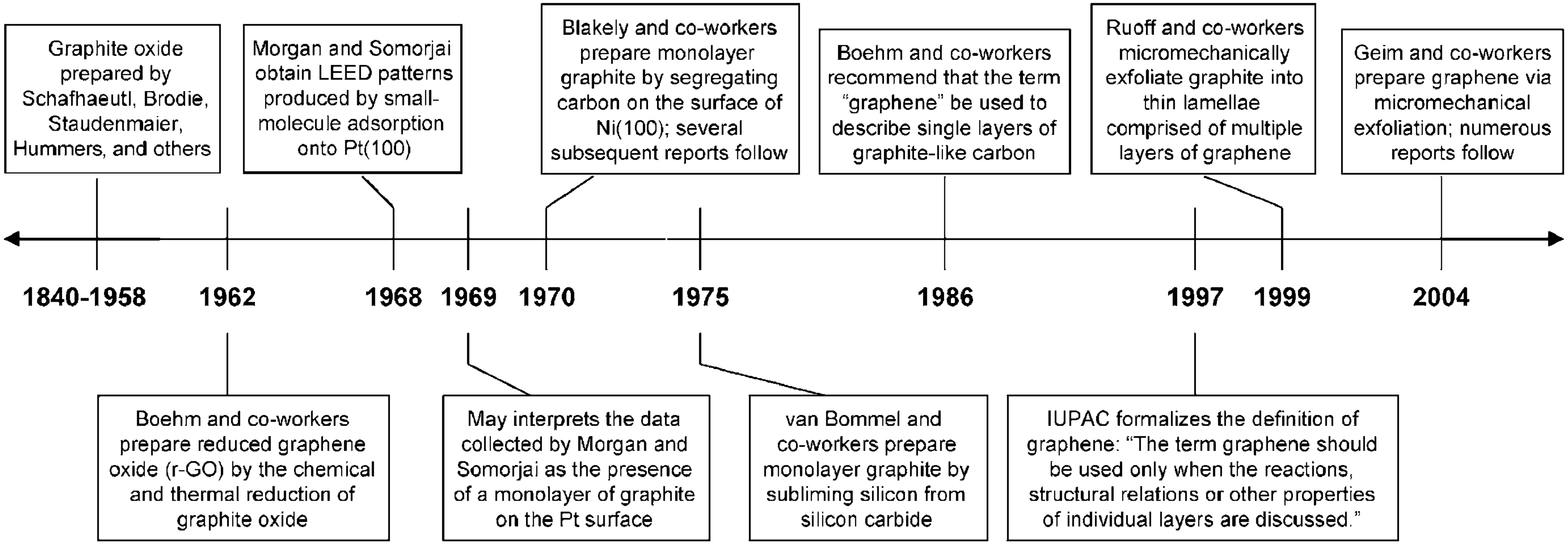




K.S. Novoselov et al., Science 306, 666 (2004)

The rise of graphene

Graphene (however) has quite a long history behind

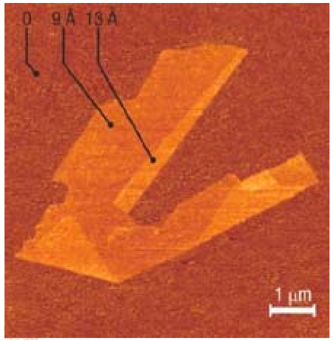


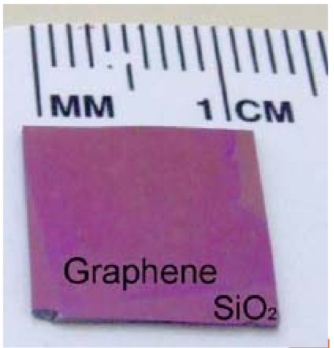
D. Dreyer et al., Angew. Chem. Int. Ed. 49, 9336 (2010)

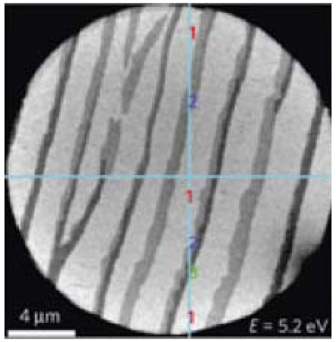
The rise of graphene

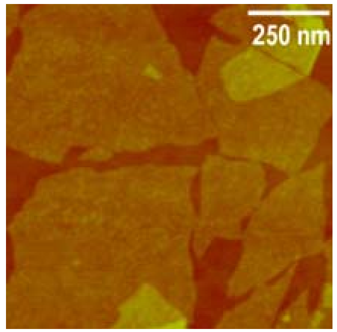
There are many graphenes today in the market with different production schemes

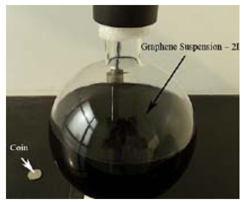
Method	Mechanical exfoliation of graphite	Growth on metal substrates	Decomposition of SiC	Chemical exfoliation of graphite	Reduction of graphene oxide











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The rise of graphene

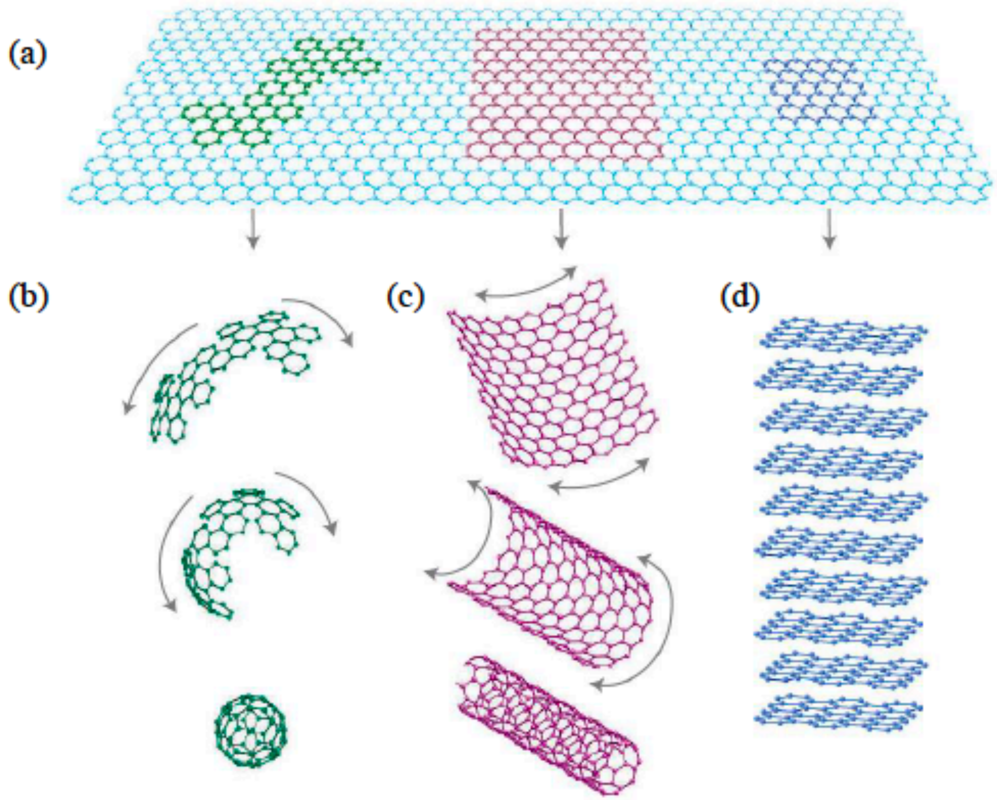
There are many graphenes today in the market with different production schemes

Method	Mechanical exfoliation of graphite	Growth on metal substrates	Decomposition of SiC	Chemical exfoliation of graphite	Reduction of graphene oxide
Quality	Excellent	Good	Good	Average	
Size	10-100 μm	∞	SiC wafer size	nm to μm	nm to μm
Transfer	Yes	Yes	No	Yes	Yes
Scalability	No	Yes	Yes	Yes	Yes

D. Dreyer et al., Angew. Chem. Int. Ed. 49, 9336 (2010)

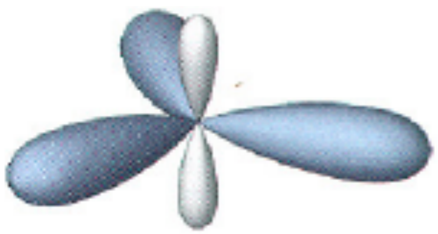
The rise of graphene

Graphene as a carbon allotrope



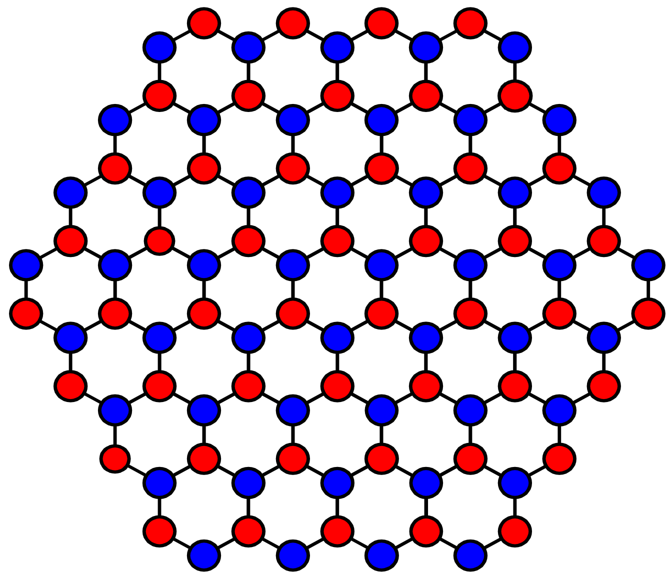
Graphene. Electronic structure

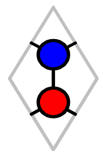
Carbon $^{6}C = 1s^2\, 2s^2\, 2p^2$
Mixing of 2s, $2p_x$, $2p_y$, $2p_z$ orbitals



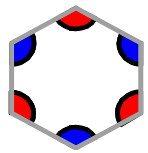
3 sp^2 orbitals
1 p_z orbital

Hexagonal lattice
1 p_z orbital at each site





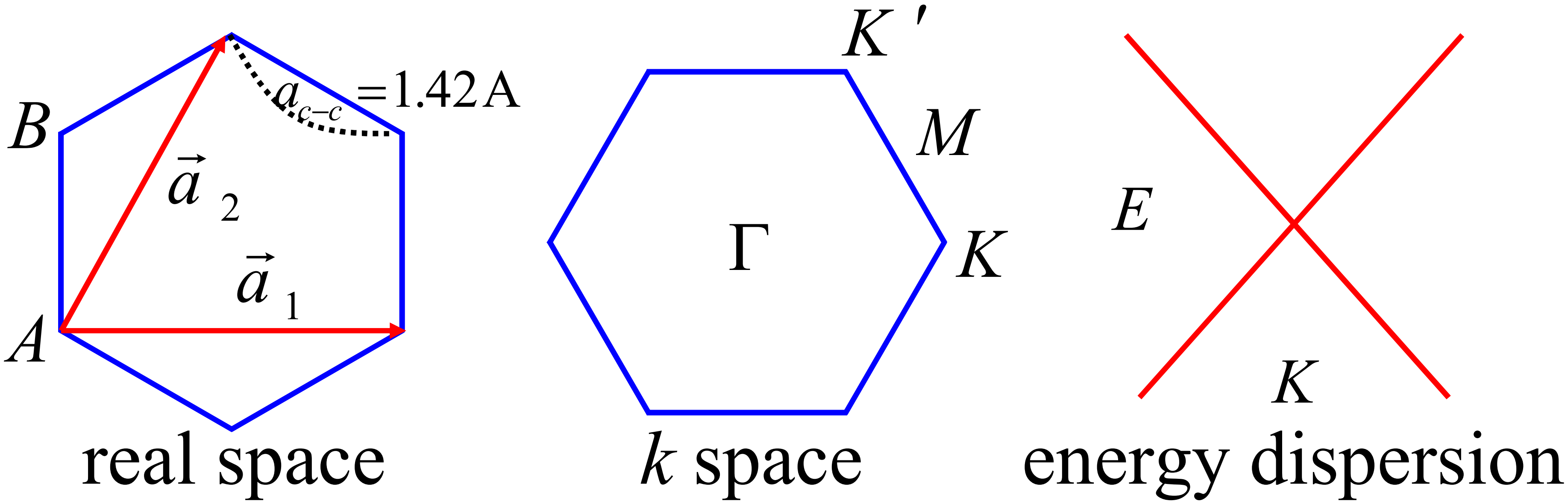
Two atoms



1/3 each of 6 atoms = 2 atoms

Graphene. Electronic structure

The energy bands of graphene at low energies are described by a 2D Dirac-like equation with linear dispersion near K/K' in k space

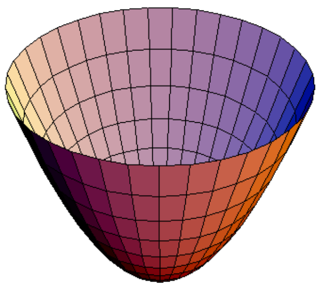


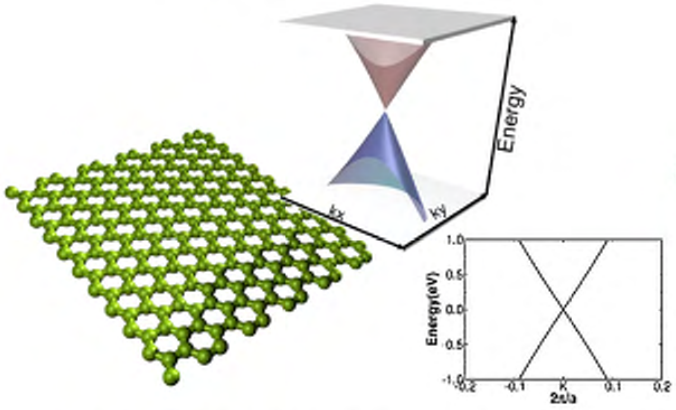
Graphene. Electronic structure

Graphene is so special (for us) because of the Dirac fermions and its peculiar DOS

In standard conductors, $E(p)=p^2/2m$

In graphene, instead, $E(p)=vp$





Graphene. Electronic structure

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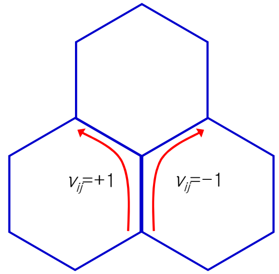
In standard conductors, $E(p)=p^2/2m$

In graphene, instead, $E(p)=vp$

Electrons behave as relativistic massless particles

Graphene. Electronic structure

Pseudo-spin represents carriers in indiscernible sub-lattices

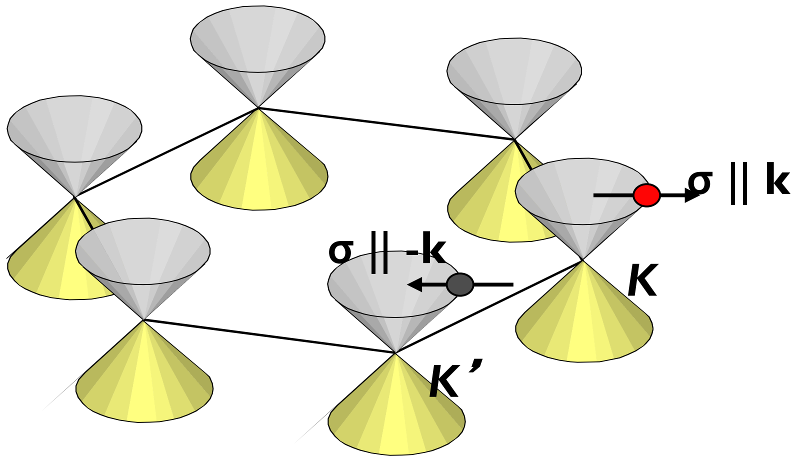


Hamiltonian with pseudospin-1/2 parallel or anti-parallel to momentum (K, K')

Orbits in k-space have Berry's phase of π

$$H_K = \hbar v_F \vec{\sigma} \cdot \vec{k} = \hbar v_F \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix}$$

$$H_{K'} = \hbar v_F \vec{\sigma}^t \cdot \vec{k}$$



Partial summary

Graphene appears as a product of an on-going research in electronic materials

Disruptive electronic structure unheard of in other materials

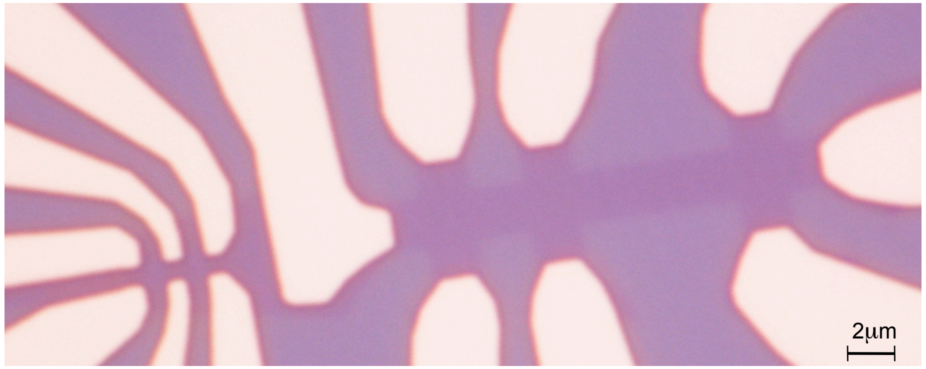
Theoreticians love it. They can apply all they had already calculated!

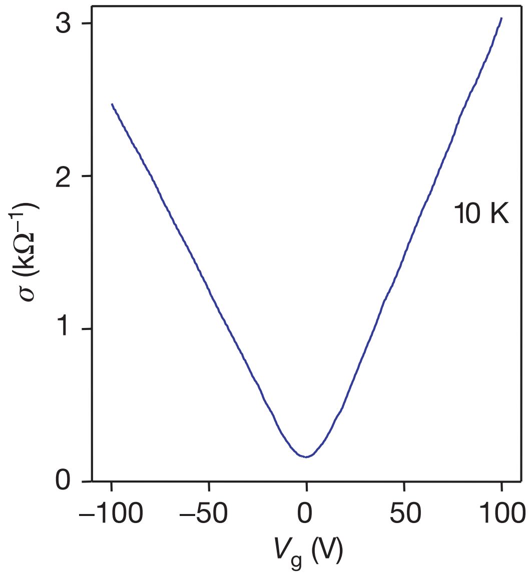
New materials lead to new physics

Now we can move to the electronic measurements

Graphene. Electronic measurements

Early measurements of carrier mobility in field-effect transistor geometries





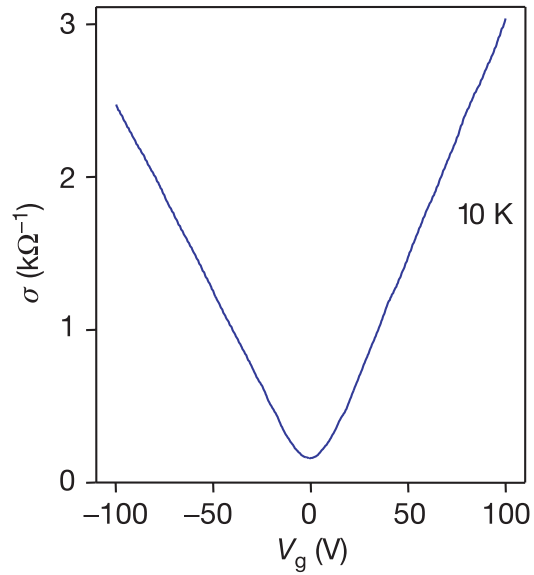
$$\rho^{-1} = \sigma = ne\mu$$

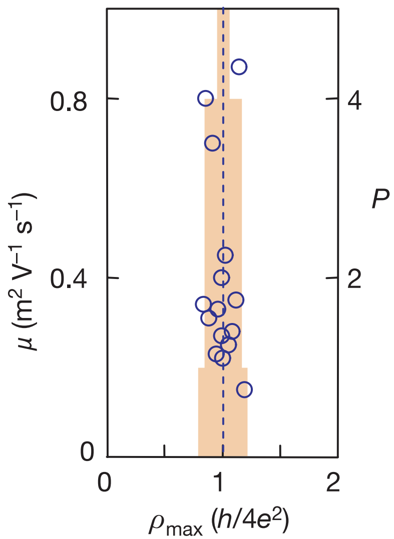
Mobility in non-optimized samples around 15,000 $cm^2/V.s$
[limited by scatering with defects]

K.S. Novoselov et al., Nature 438, 197 (2005) [also Y. Zhang et al., Nature 438, 201 (2005)]

Graphene. Electronic measurements

Vanishing DOS at Vg=0 should imply zero conductivity. Experimentally not found





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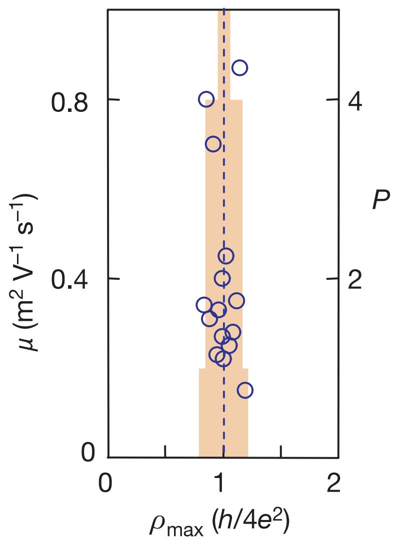


$$\rho_{\max} = 6.5k\Omega \approx \frac{h}{4e^2}$$

Mott's argument and absence of localization (Dirac):
mean free path l can never be shorter than their wavelength λ_F

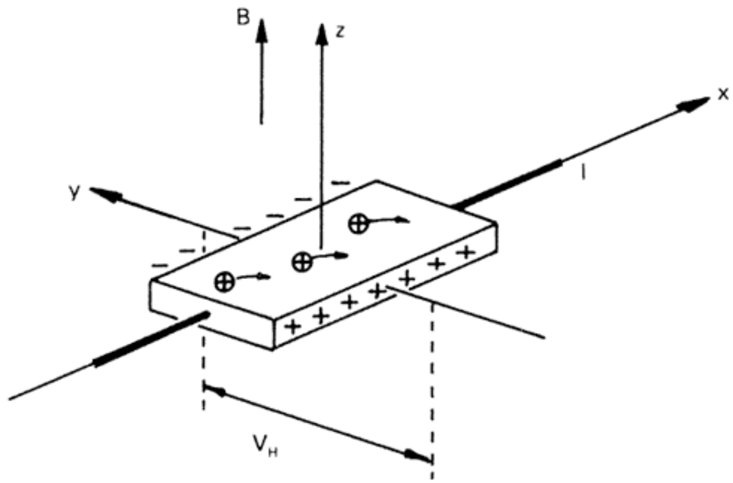
$$\sigma = ne\mu = ne^2 v_F l = \left(\frac{e^2}{h}\right) k_F l$$

K.S. Novoselov et al., Nature 438, 197 (2005) [also Y. Zhang et al., Nature 438, 201 (2005)]

Graphene. Into the quantum Hall regime

Hall-effect measurements in high magnetic fields

In a free-electron system, leads to the classical Hall effect

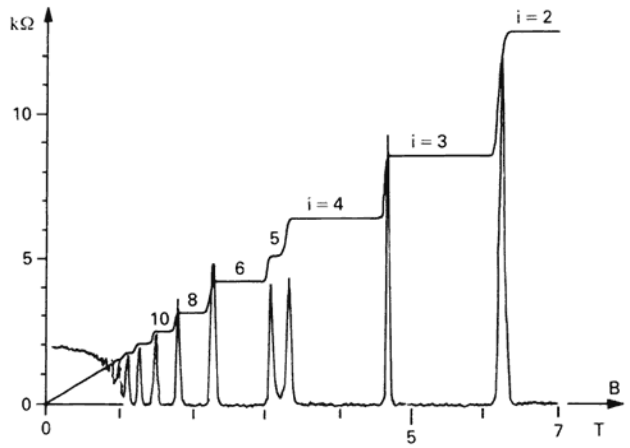


Graphene. Into the quantum Hall regime

Hall-effect measurements in high magnetic fields

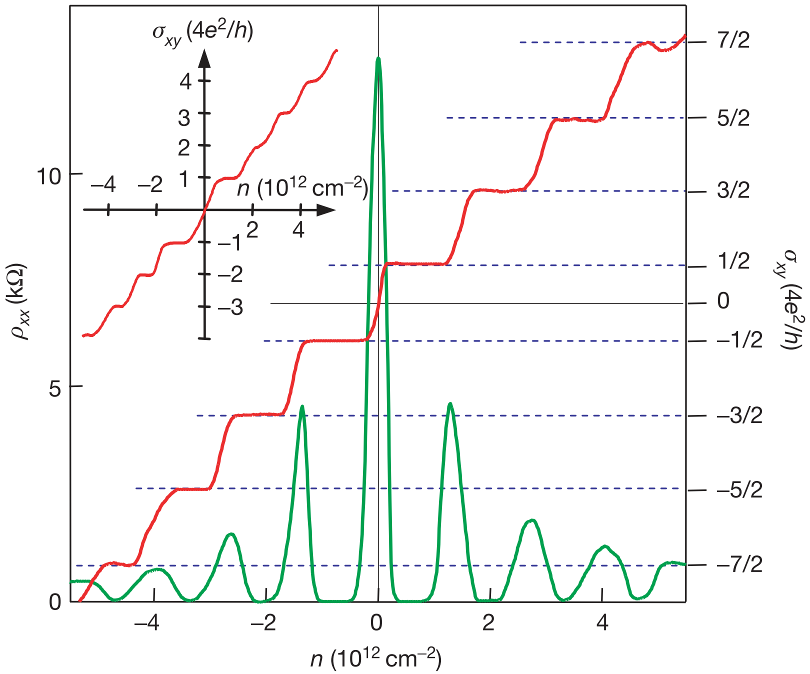
In a free-electron system, leads to the classical Hall effect

In a 2DEG, can lead to the quantum Hall effect



Graphene. Into the quantum Hall regime

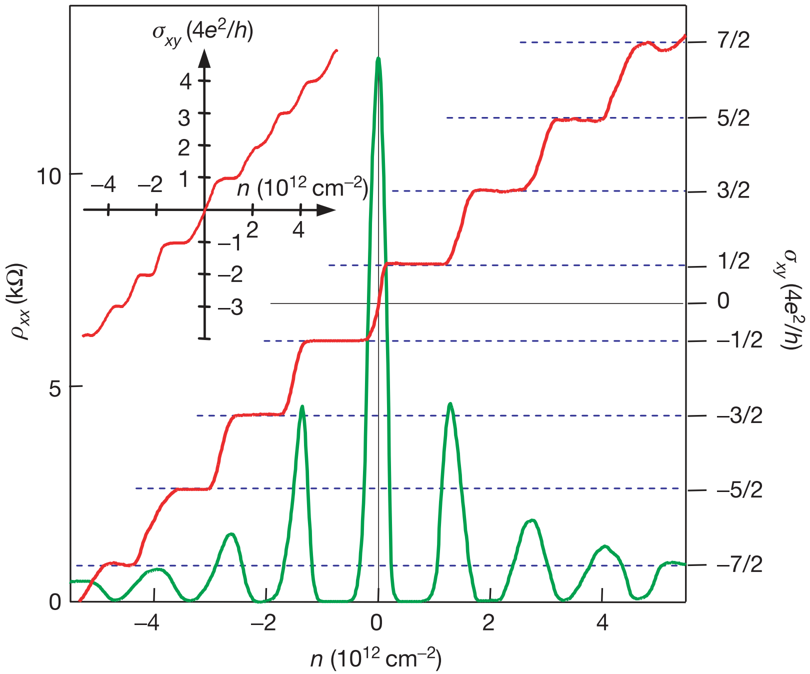
Hall-effect measurements for monolayer graphene



K.S. Novoselov et al., Nature 438, 197 (2005) [also Y. Zhang et al., Nature 438, 201 (2005)]

Graphene. Into the quantum Hall regime

Half-integer quantum Hall effect. Filling predicted for massless Dirac fermions

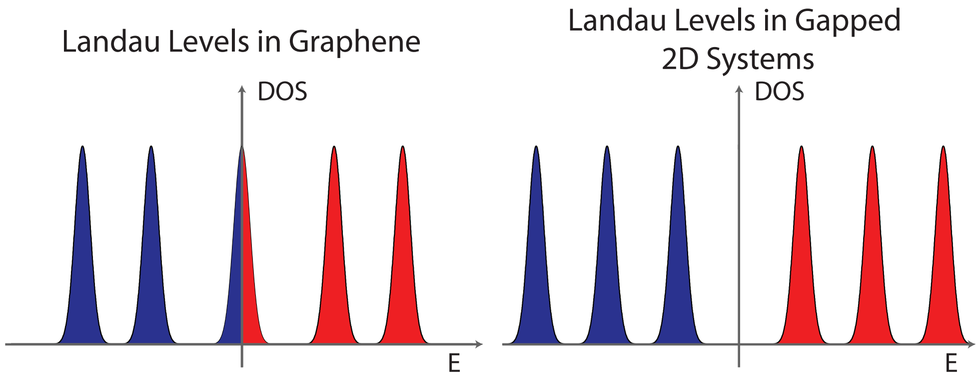


K.S. Novoselov et al., Nature 438, 197 (2005) [also Y. Zhang et al., Nature 438, 201 (2005)]

Graphene. Into the quantum Hall regime

Half-integer quantum Hall effect coming from hole-electron symmetry

$$-v_F(\vec{p}+e\vec{A})\cdot\sigma\psi(\vec{r}) = E\psi(\vec{r}) \qquad E_n = \sqrt{2e\hbar v_F^2|n|B}$$



$$\sigma_{xy} = 4(n+1/2)\,e^2/h = 2, 6, 10\ldots e^2/h$$

→ Berry's phase of π

K.S. Novoselov et al., Nature 438, 197 (2005) [also Y. Zhang et al., Nature 438, 201 (2005)]

Partial summary

The electronic properties of graphene are truly novel

Electronic measurements reflect the electronic structure and the DOS

Outstanding mobility for a 2D (exposed!) layer

Quantum Hall effect gives us an insight into deeper physics

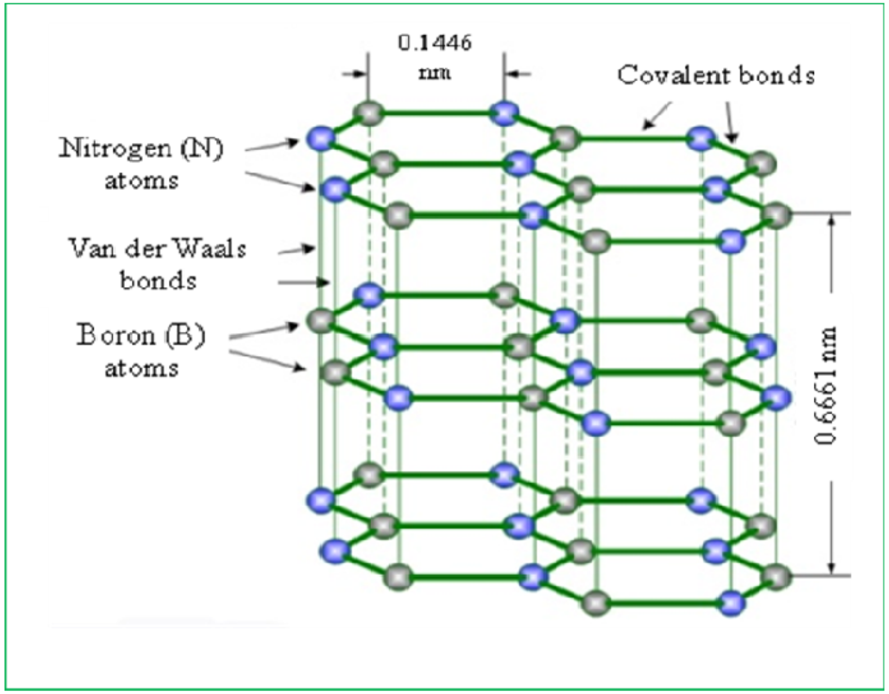
Graphene (artificial) multi-structures

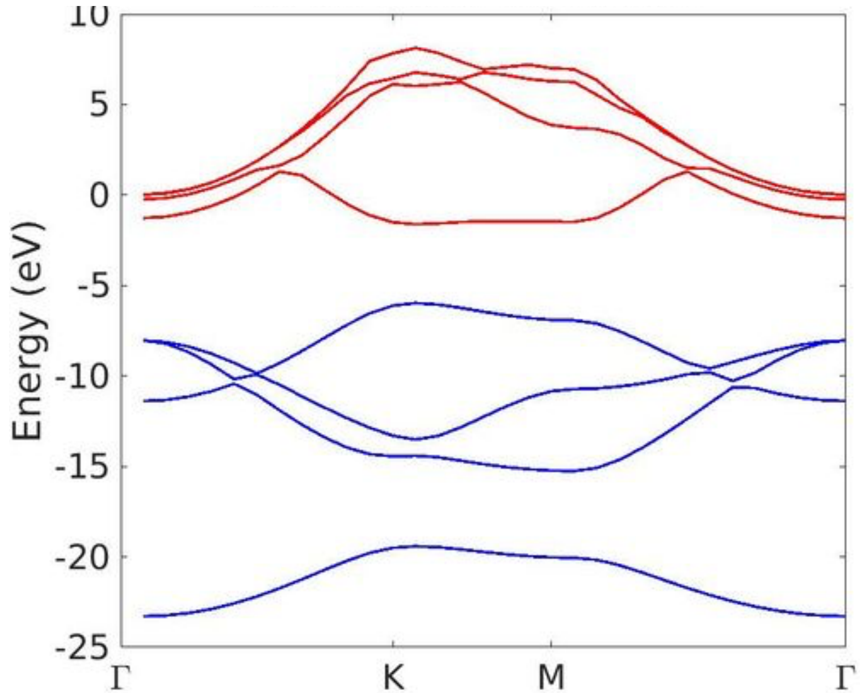
Graphene layers can be sequentially stacked and rotated

New research field called "van der Waals heterostructures"

Graphene (artificial) multi-structures

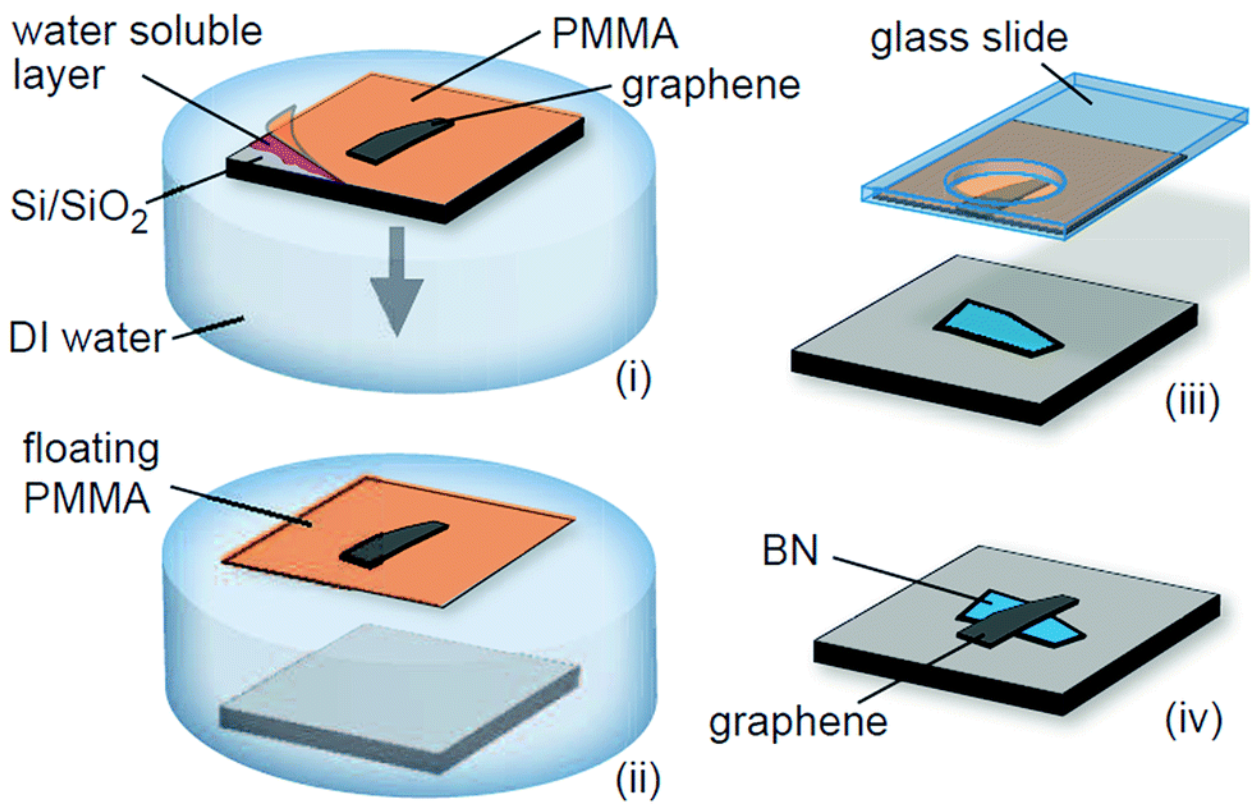
Hexagonal-BN as an insulating equivalent of graphene





Graphene (artificial) multi-structures

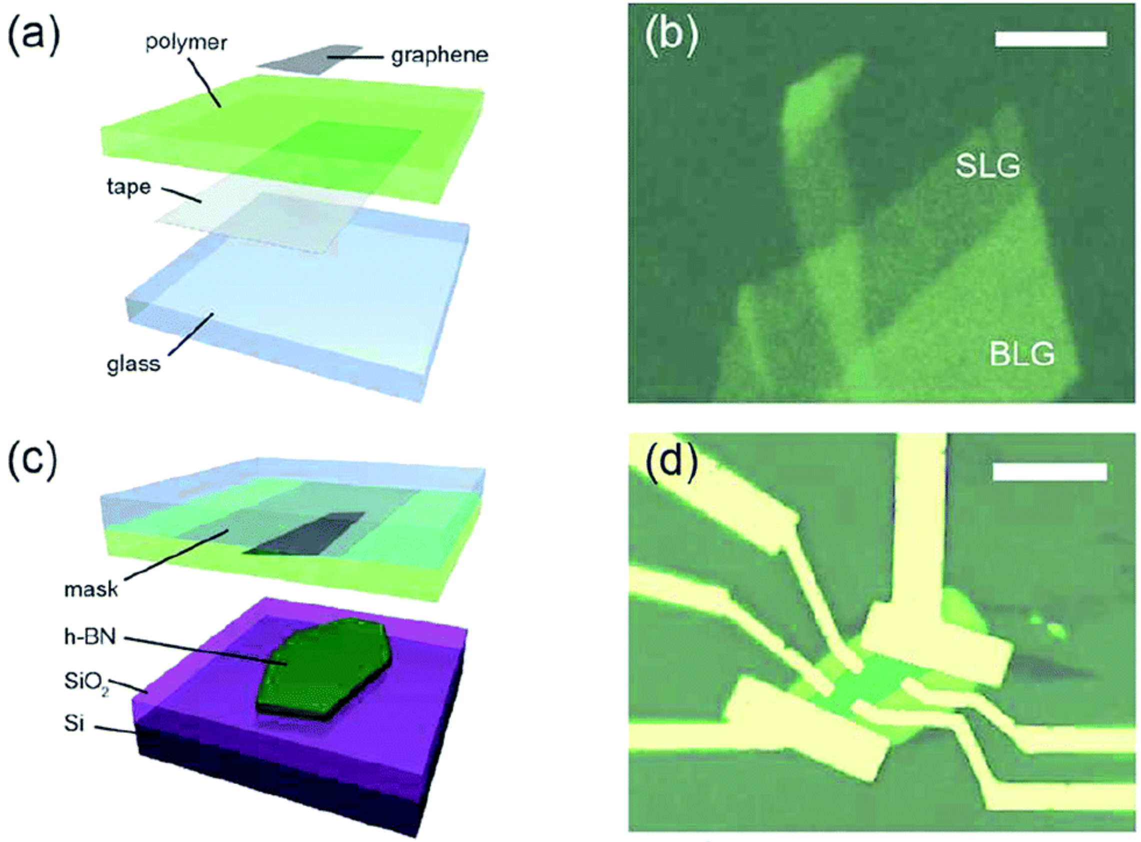
Graphene and h-BN layers can be sequentially stacked



C. R. Dean et al. , Nature, 497, 598 (2013)

Graphene (artificial) multi-structures

Graphene and h-BN layers can be sequentially stacked

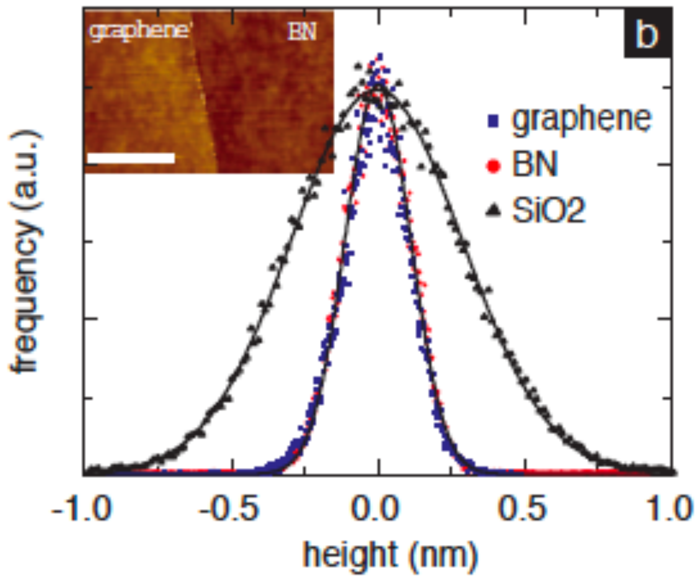


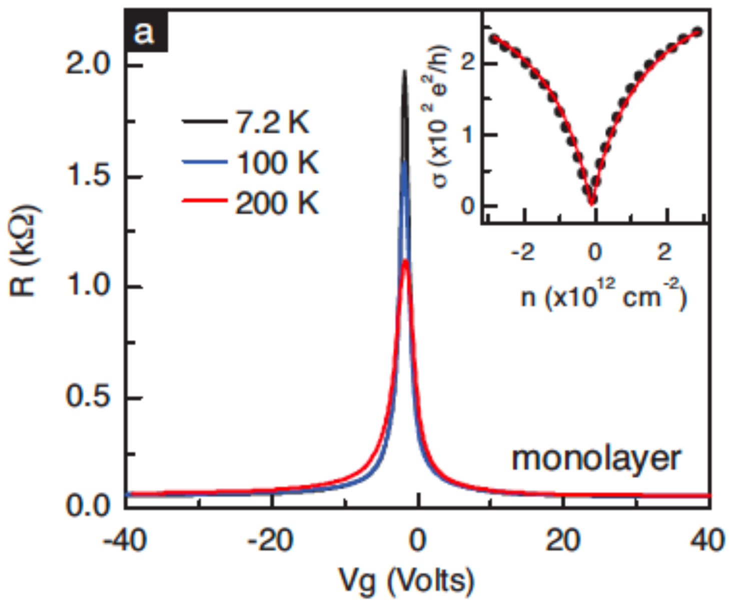
P. J. Zomer et al., Appl. Phys. Lett. 99, 1643 (2011)

Graphene (artificial) multi-structures

Electronic properties are greatly enhanced in comparison with SiO_2 substrates

Mobility reaching 100,000 $cm^2/V.s$ in some cases. Limited by phonons (not defects)

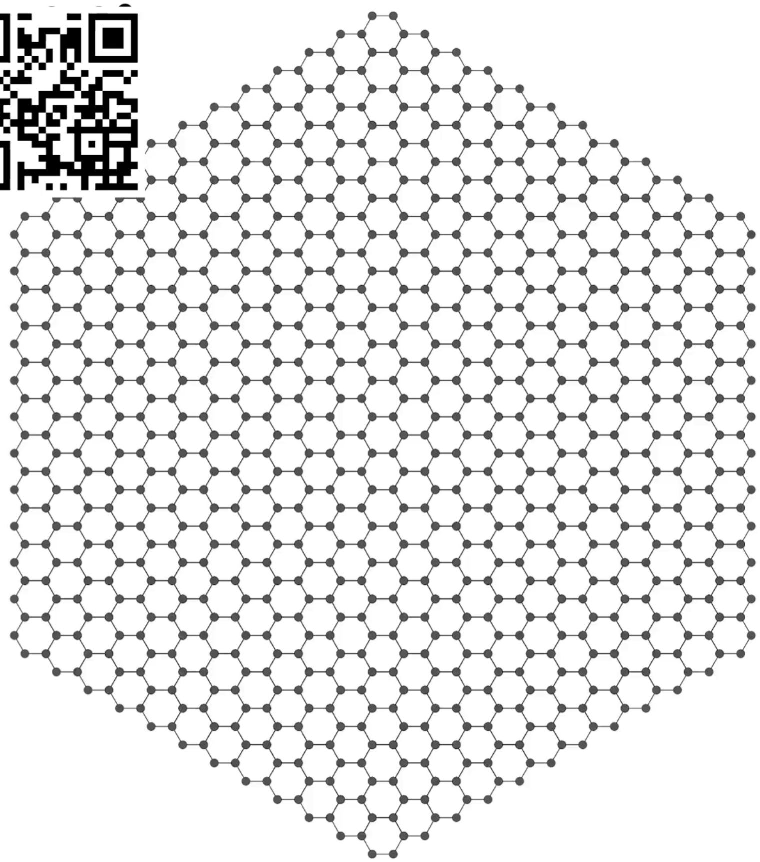




C. R. Dean et al. , Nature, 497, 598 (2013)

Graphene bilayers

Graphene layers can be sequentially stacked and rotated

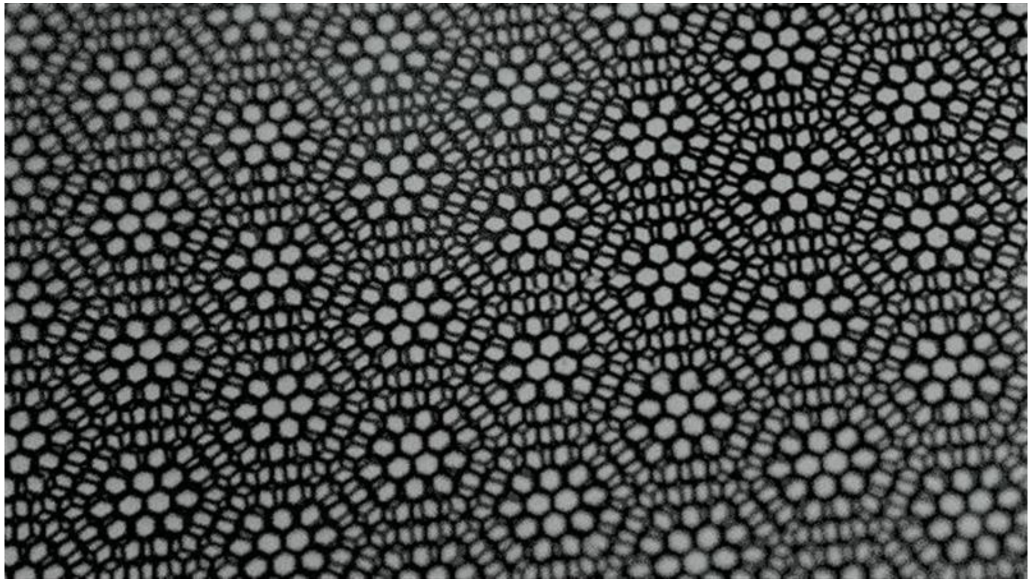


PMende [You Tube]

Graphene bilayers

Graphene layers can be sequentially stacked and rotated

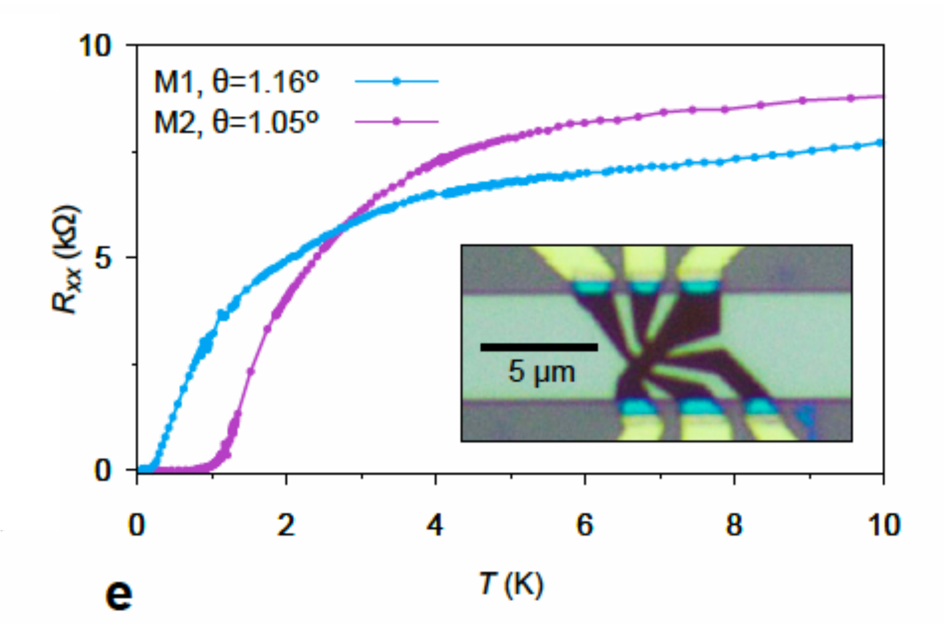
The Moire's pattern depend on the angle between the layers

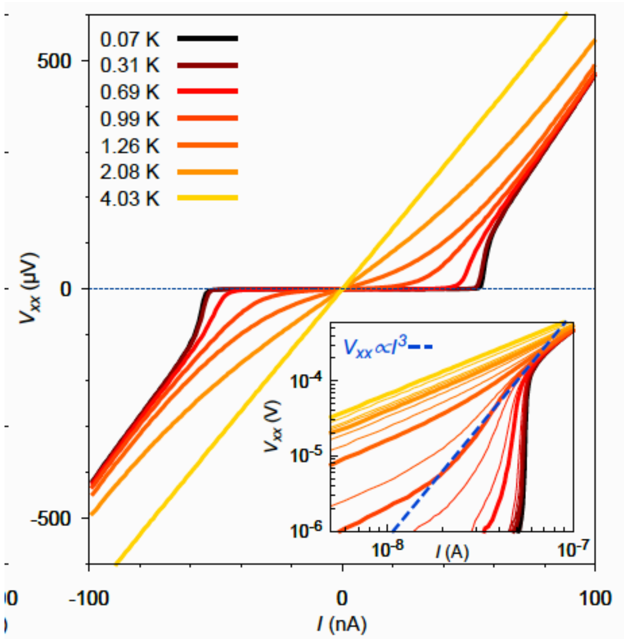


P. Jarillo's group (MIT)

Graphene bilayers

Magic-angle bilayer graphene samples show superconductivity

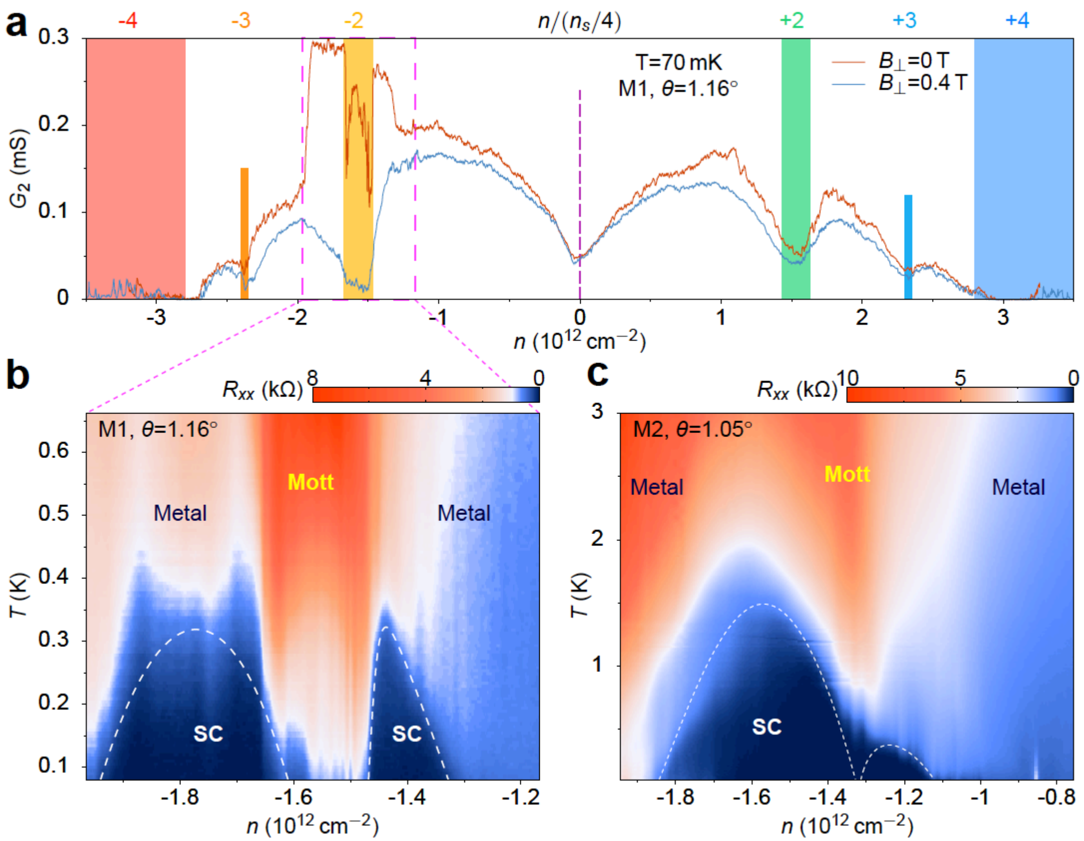




Y. Cao, P. Jarillo et al, Nature 556, 43-50 (2018).

Graphene bilayers

Transport properties can be modulated with doping (by gating) on a single sample



Y. Cao, P. Jarillo et al, Nature 556, 43-50 (2018).

Partial summary

Fabrication of van der Waals heterostructures is possible (more on this later)

The electronic properties of graphene can be tuned by changing the substrate

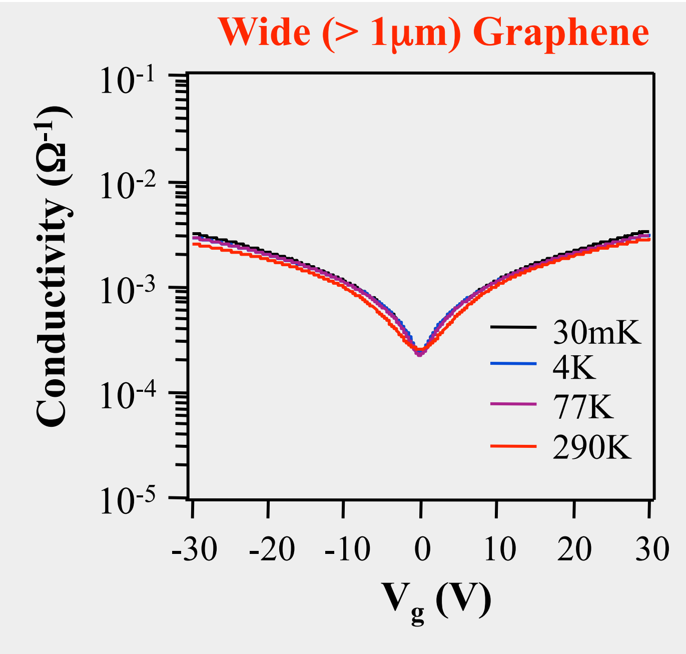
Bilayer graphene offers new exciting possibilities

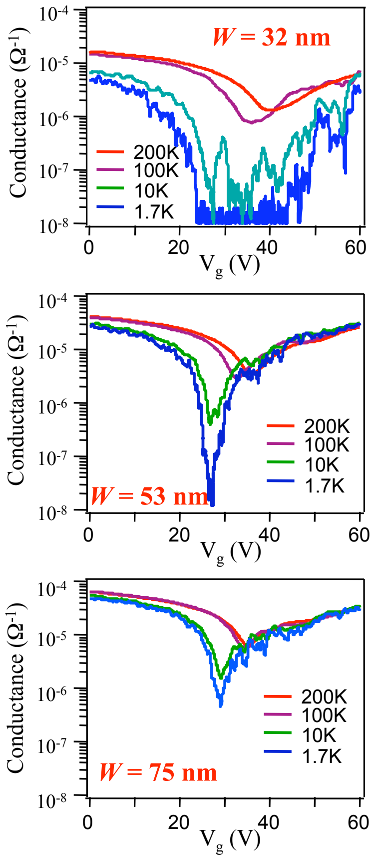
SC in bilayer graphene one of the most important recent results in CMP

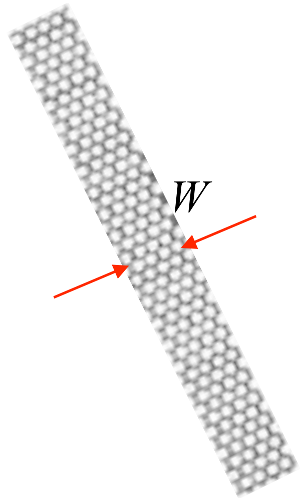
Many other effects not discussed here

Graphene nanoribbons

Trying to turn graphene into a real semiconductor by confinement







$$E_{gap} \approx \hbar v_F / W$$

M. Han et al., Phys. Rev. Lett. 98, 206805 (2007) [also X. Wang et al. , Phys. Rev. Lett. 100, 206803 (2008)]

Graphene nanoribbons

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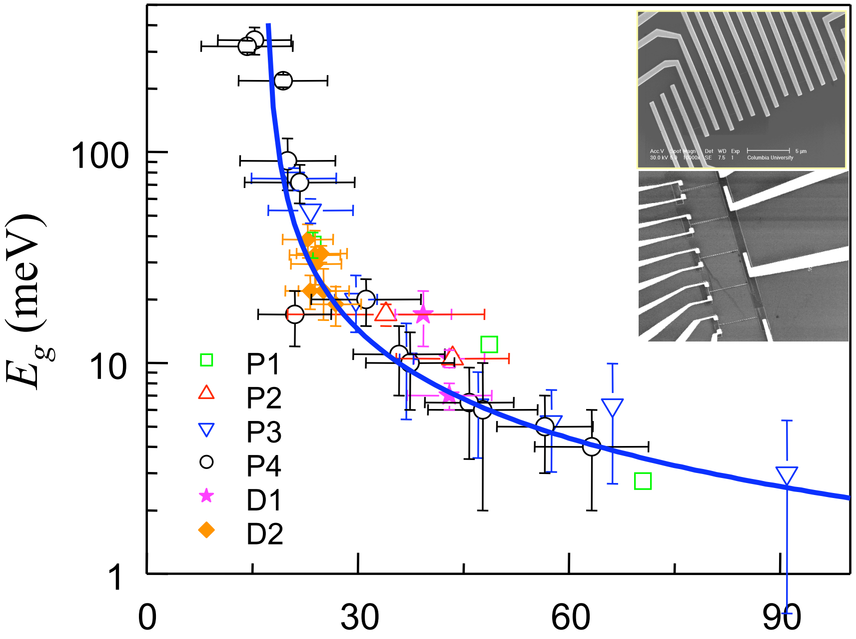

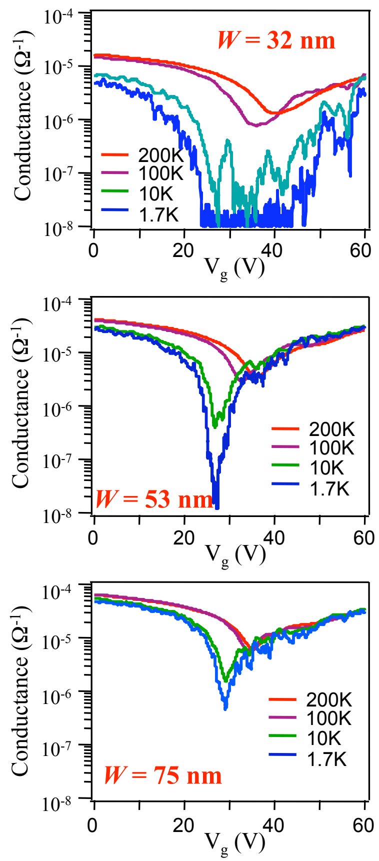

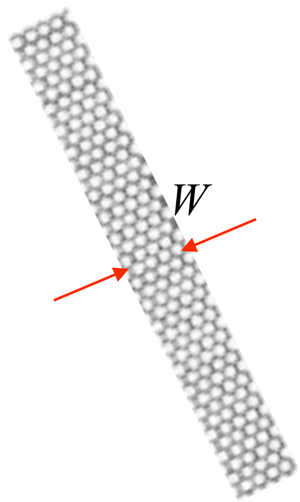

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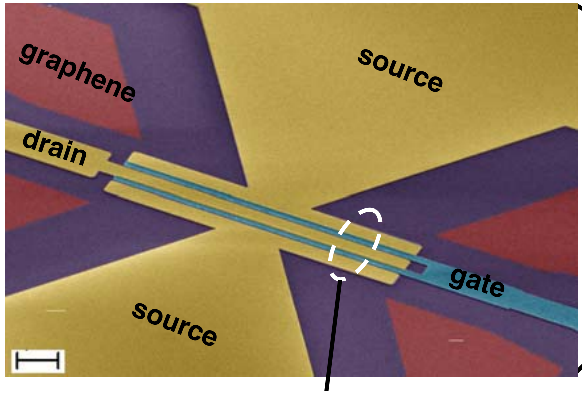
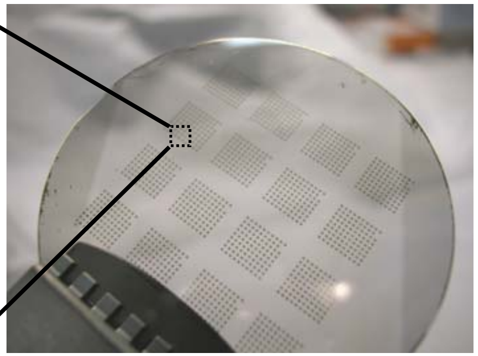
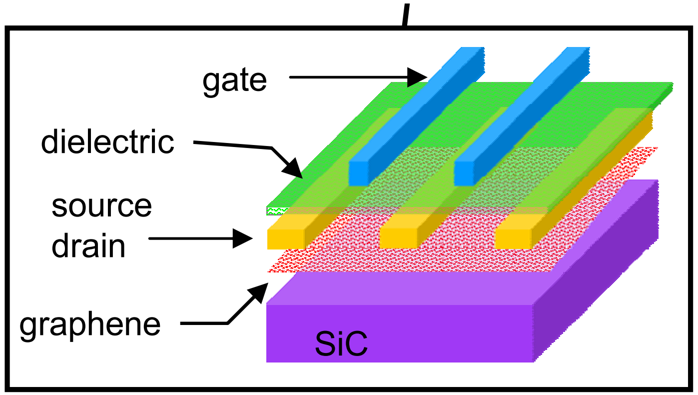
Graphene in ultra-fast electronics

Profiting from graphene high mobility for GHz electronic devices

Fabrication with SiC graphene and top gate geometry







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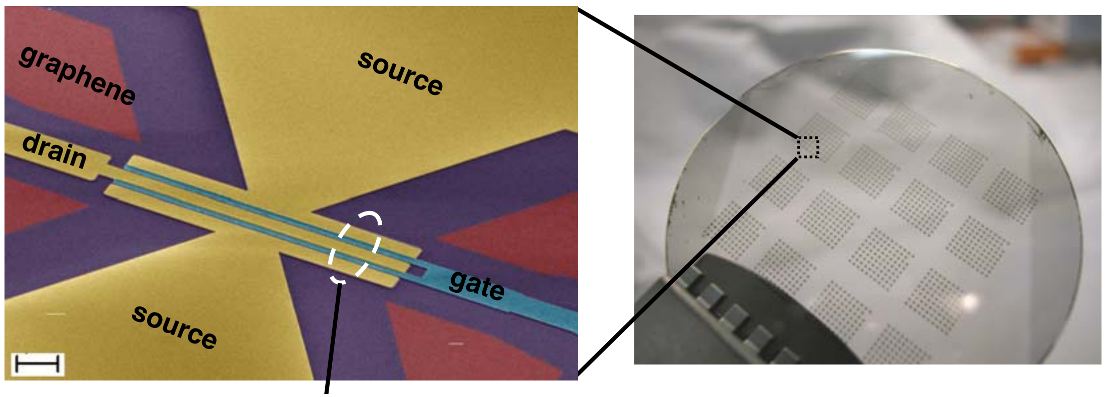
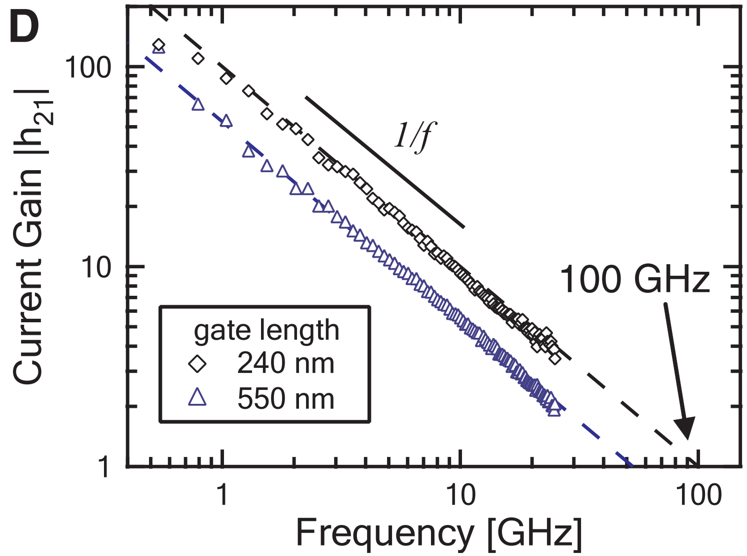




M. Han et al., Phys. Rev. Lett. 98, 206805 (2007) [also X. Wang et al. , Phys. Rev. Lett. 100, 206803 (2008)]

Partial summary

Graphene covers much more ground than just pure simple digital electronics

It has great properties but serious drawbacks of complex solution

The lack of band gap can be critical for the future expansion of applications

Niche sectors such as spintronics or transparent electrodes are promising

Beyond graphene

We have seen graphene has several drawback (notably the absence of bandgap)

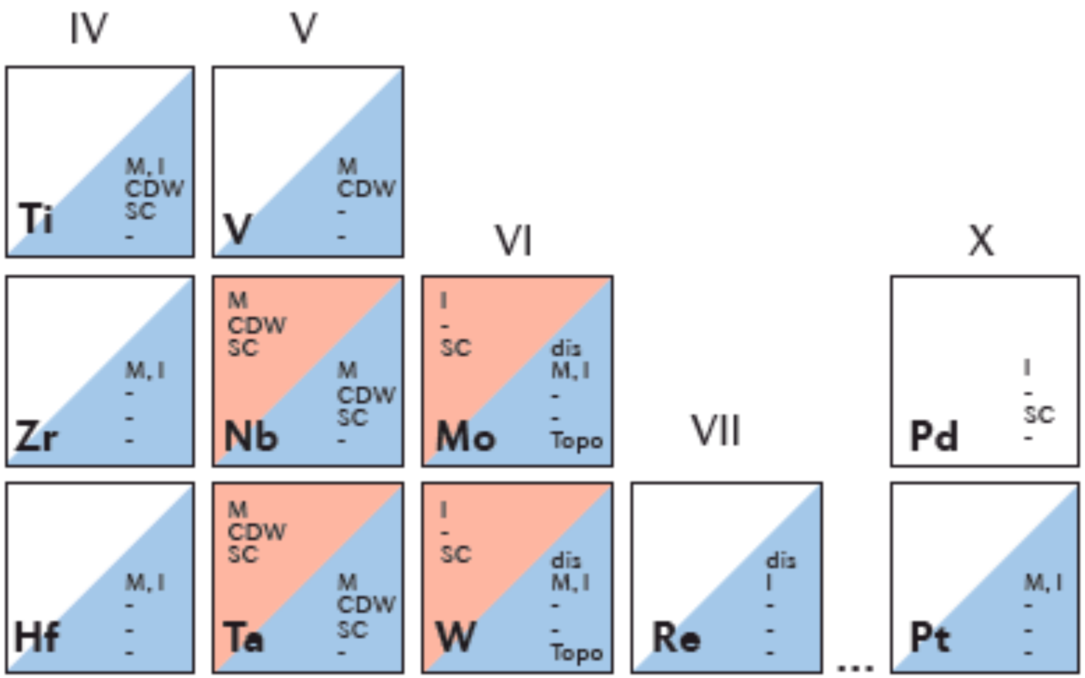
Research on graphene has stimulated work on 2D materials as a class on its own

New (and revisited) materials are creating a new field of research

Many materials (we have seen h-BN). We will focus mostly in a particular family

Transition-metal dichalcogenides

Compounds with general formula: AX_2 (A: transition metal; X: chalcogen)



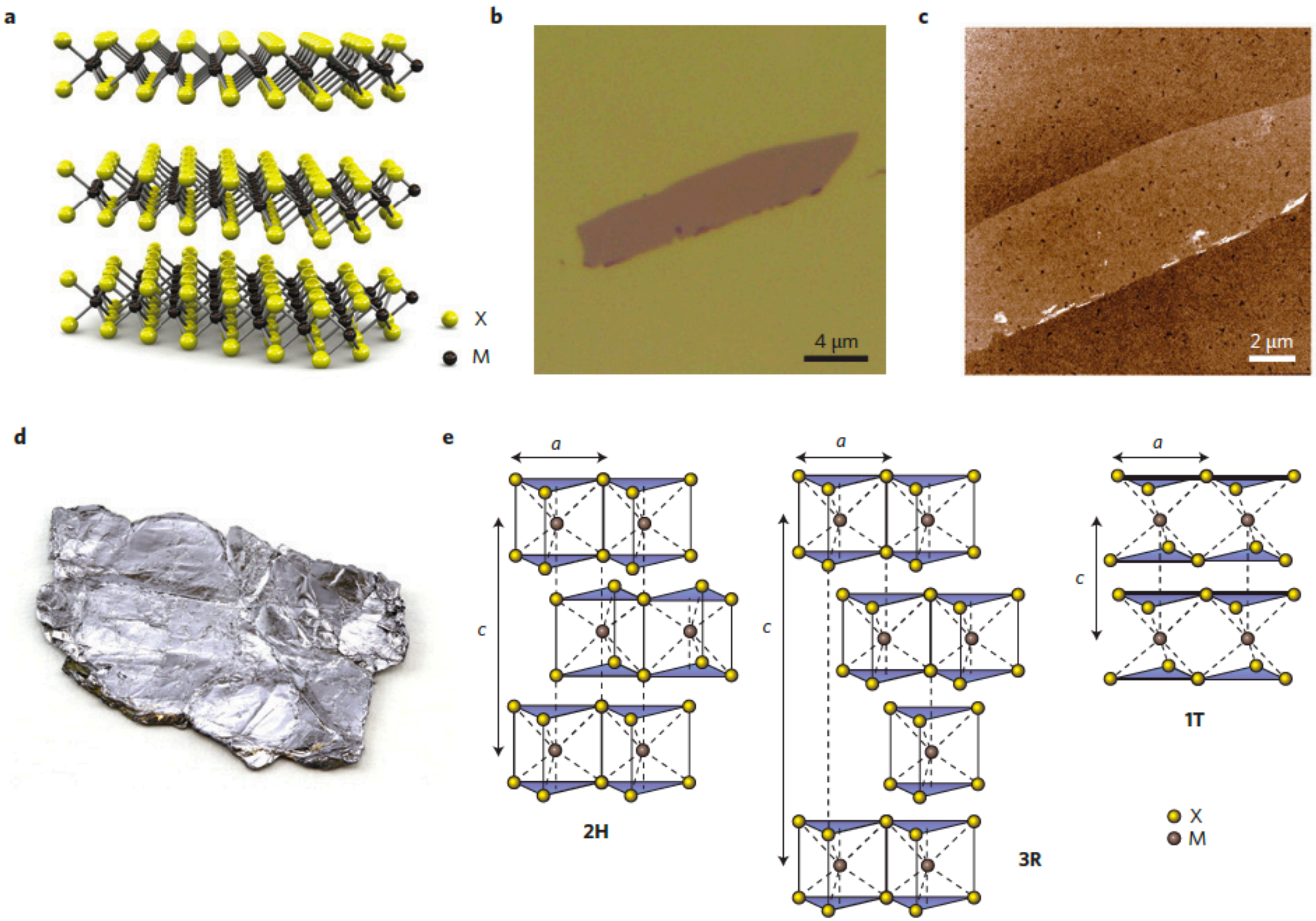
Transition-metal dichalcogenides

Compounds with general formula: AX_2 (A: transition metal; X: chalcogen)

The most common (is a mineral) is MoS_2

Layered material with different polytypes

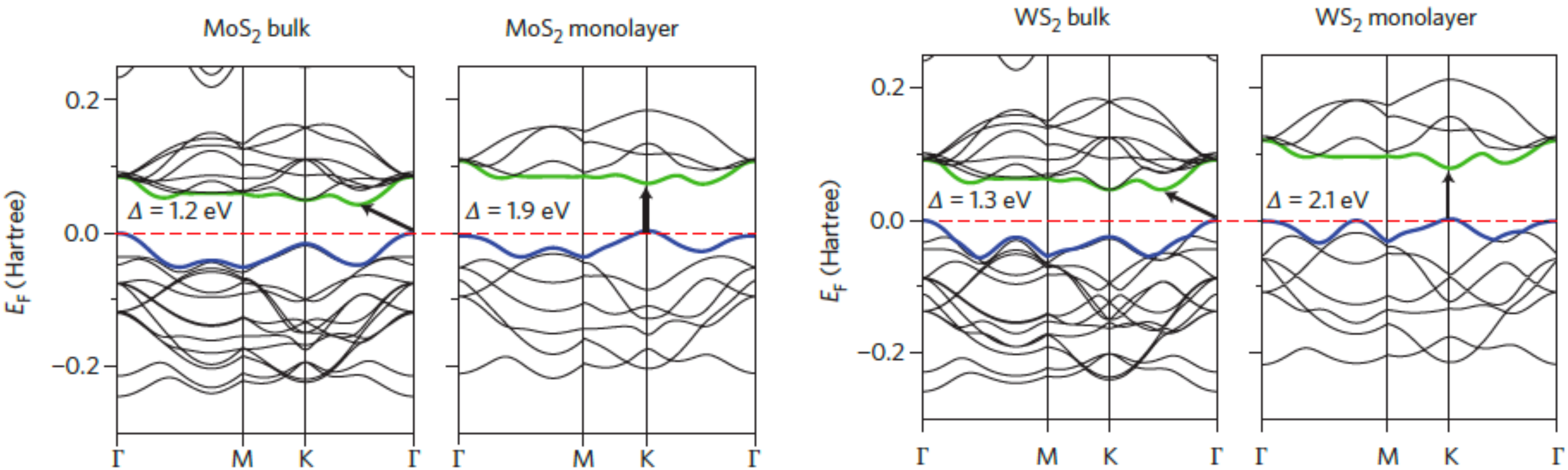
MoS_2 as a transition-metal dichalcogenide



Q.H Wang et al., Nature Nano. 7, 699 (2012)

MoS_2 as a transition-metal dichalcogenide

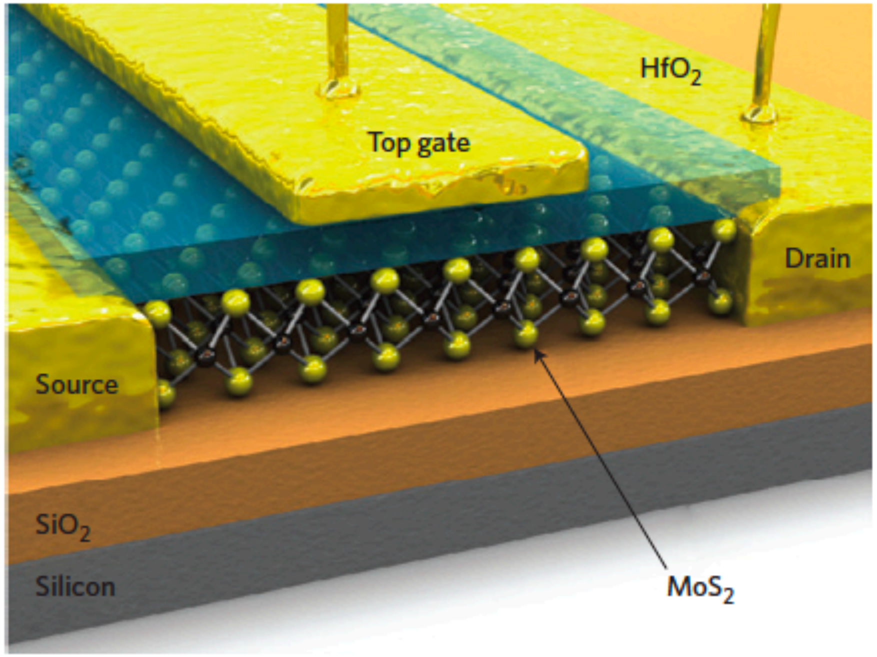
Band structure changes with dimensionality. Great tuning parameter

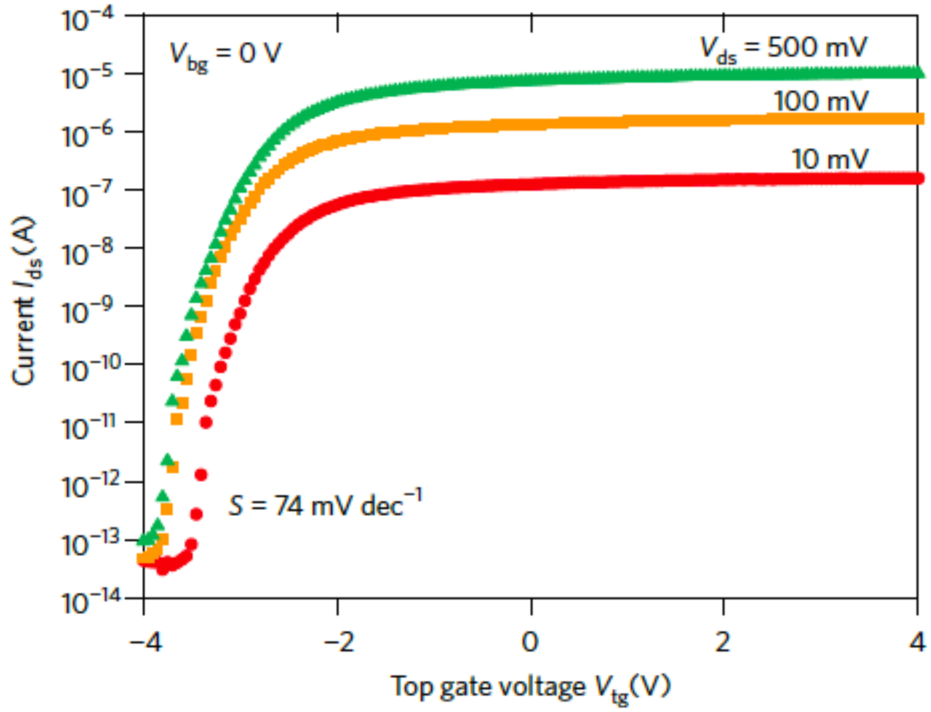


Q.H Wang et al., Nature Nano. 7, 699 (2012)

Electronics with MoS_2

MoS_2 being a true semiconductors produces true field-effect digital devices





B. Radisavljevic et al., Nature Nano. 6, 147 (2011)

Partial summary

New 2D materials beyond graphene

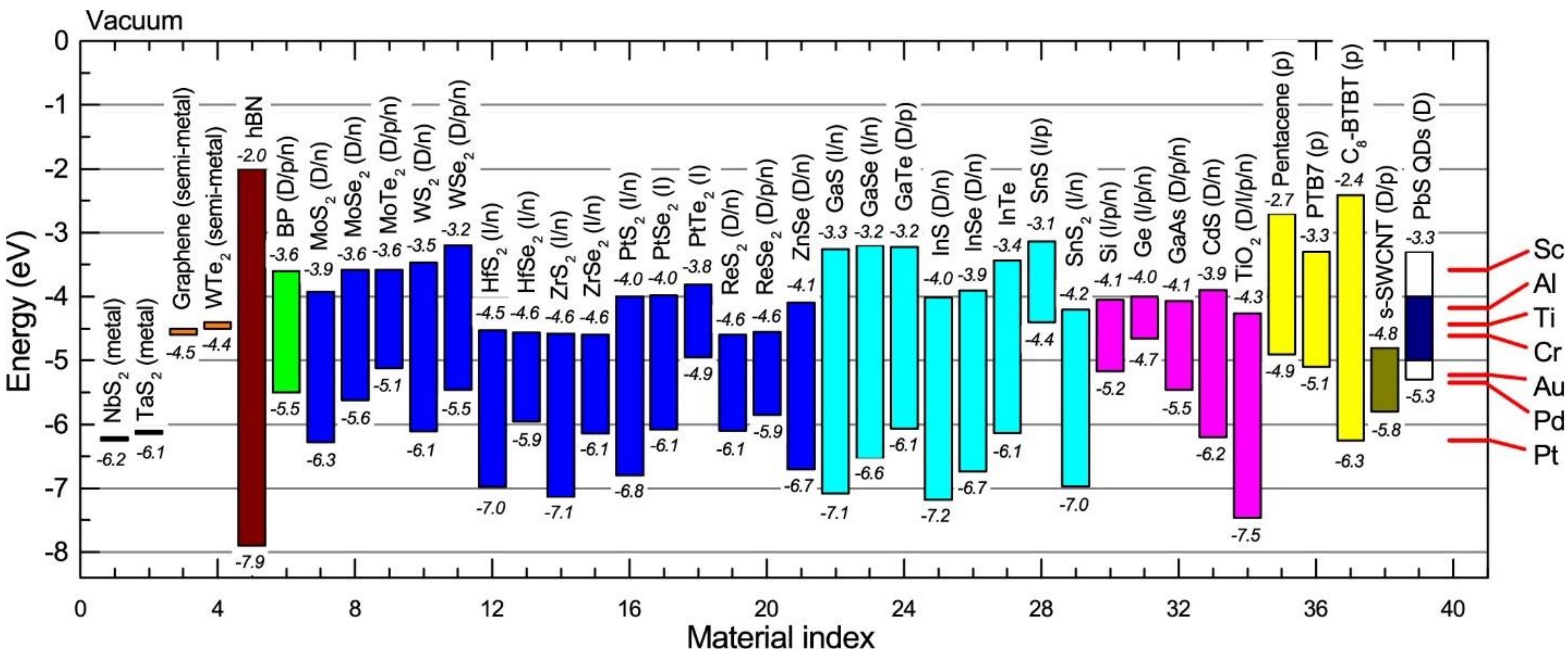
Transition-metal dichalcogenides are among the most prominent

MoS_2 is a true semiconductor

Nice electronic and optical properties revealed

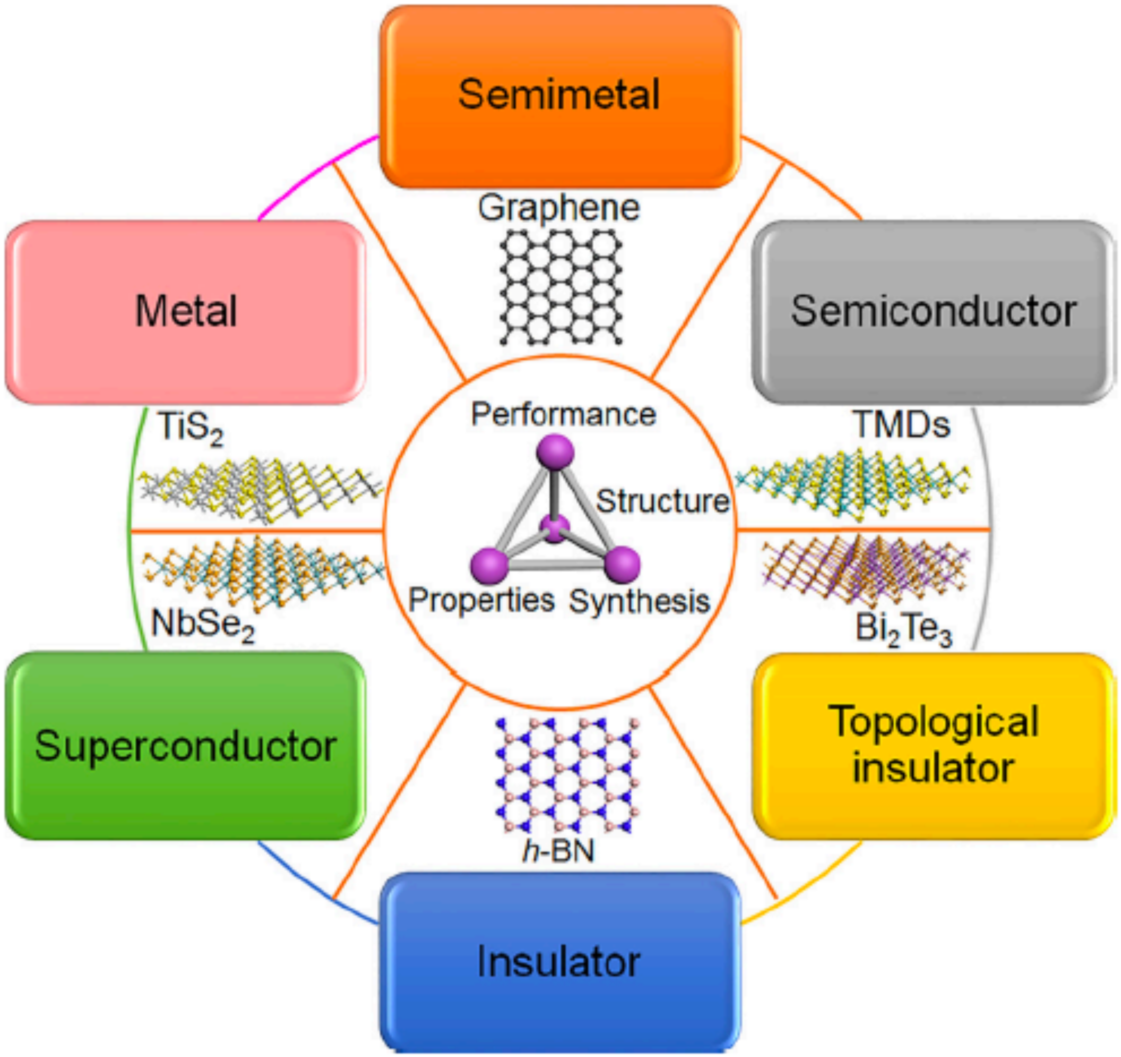
Very large family, as we will see now

Comparison of band-gap of 2D materials



V. Sanwan and M. Hersam, unpublished

Transition-metal dichalcogenides



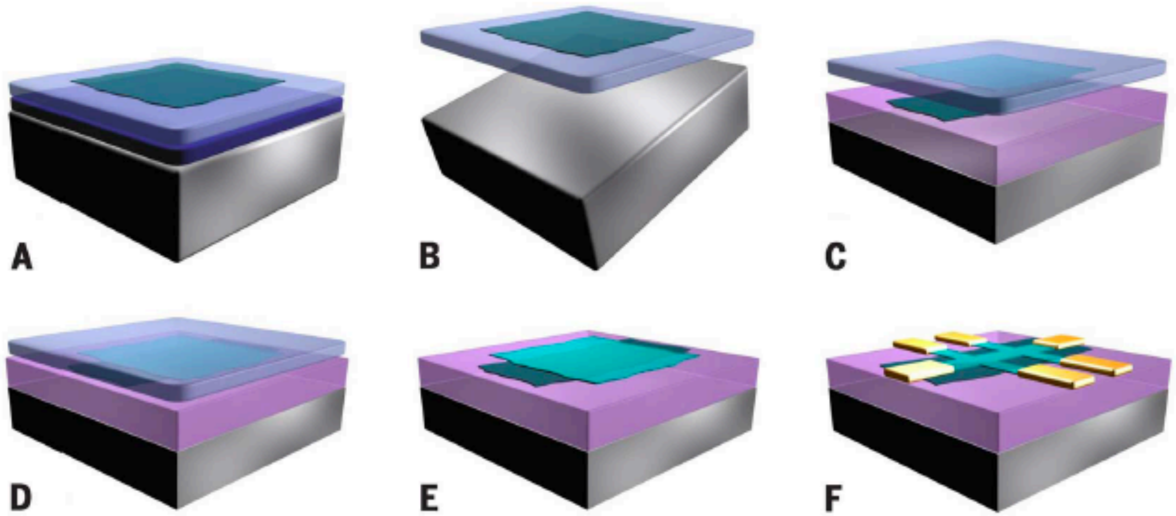
2D van der Waals heterostructure devices

Artificial purpose-designed materials by vdW epitaxy

Brief recap regarding the fabrication (similar to graphene/h-BN seen before)

2D van der Waals heterostructure devices

Wet technique schematized

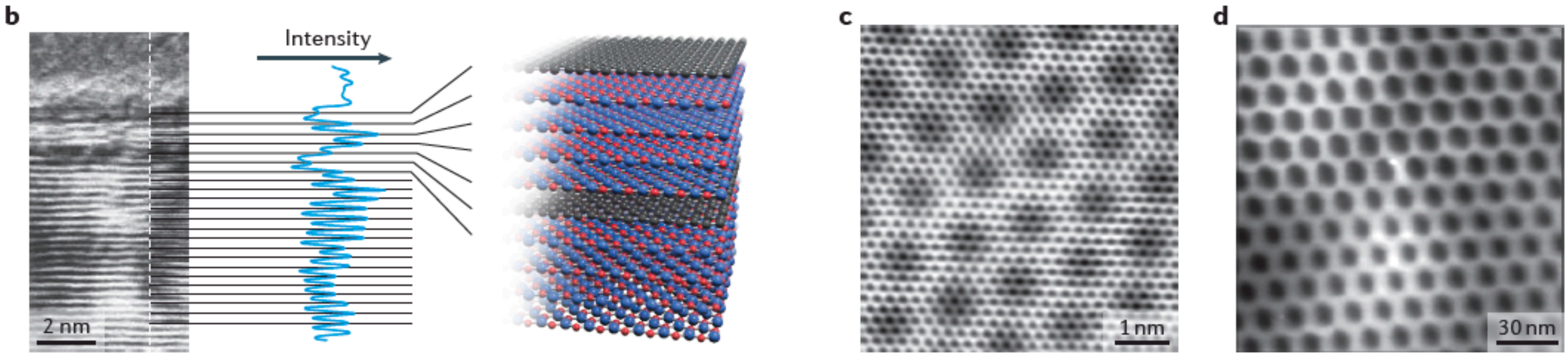


K.S. Novoselov et al., Science 353, 461 (2016)

2D van der Waals heterostructure devices

Cross-section of extraordinary homogeneity

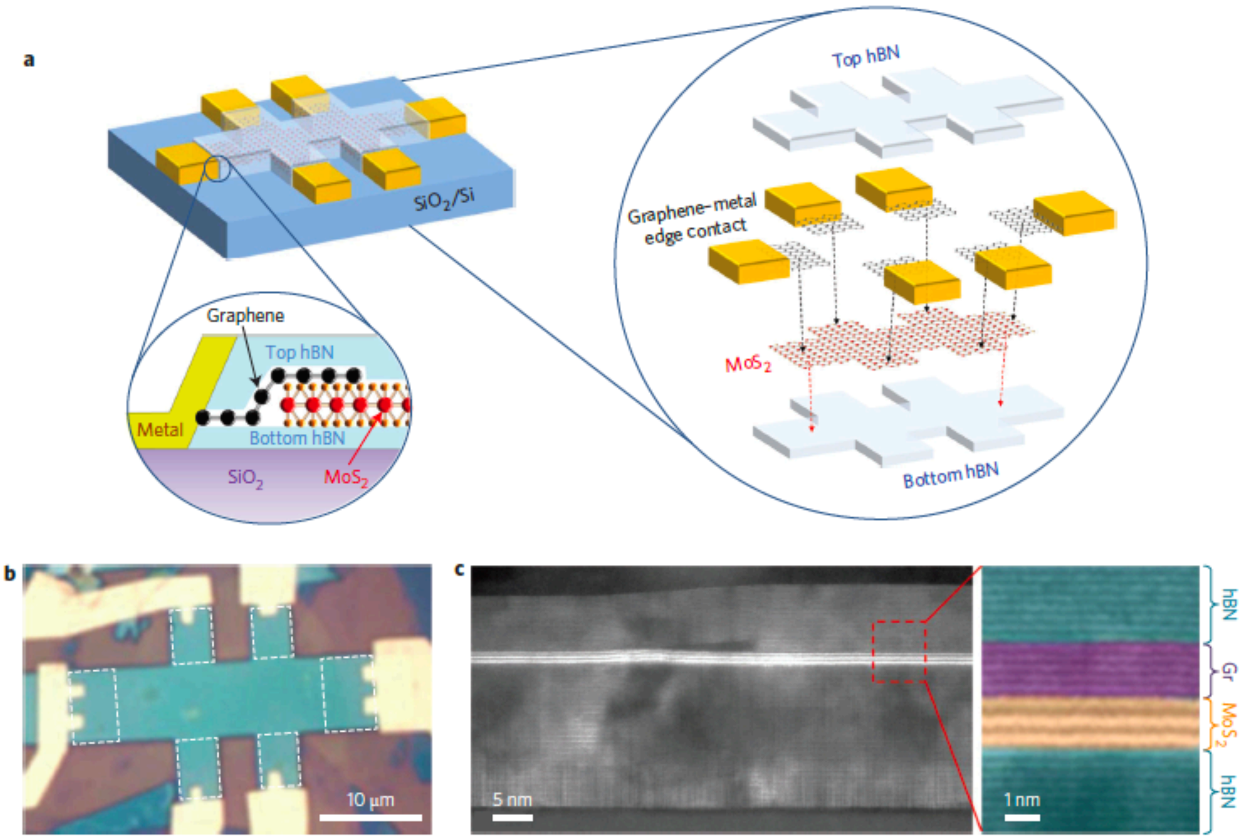
Examples in this case with graphene/h-BN (easier to observe differences and patterns)



S.J. Haigh et al., Nature Mater. 11, 764 (2012)

2D to MoS_2 electrical contacts

Fully engineered MoS2 device for reaching ultimate electronic properties



X. Cui et al., Nature Nano. 10, 534 (2015)

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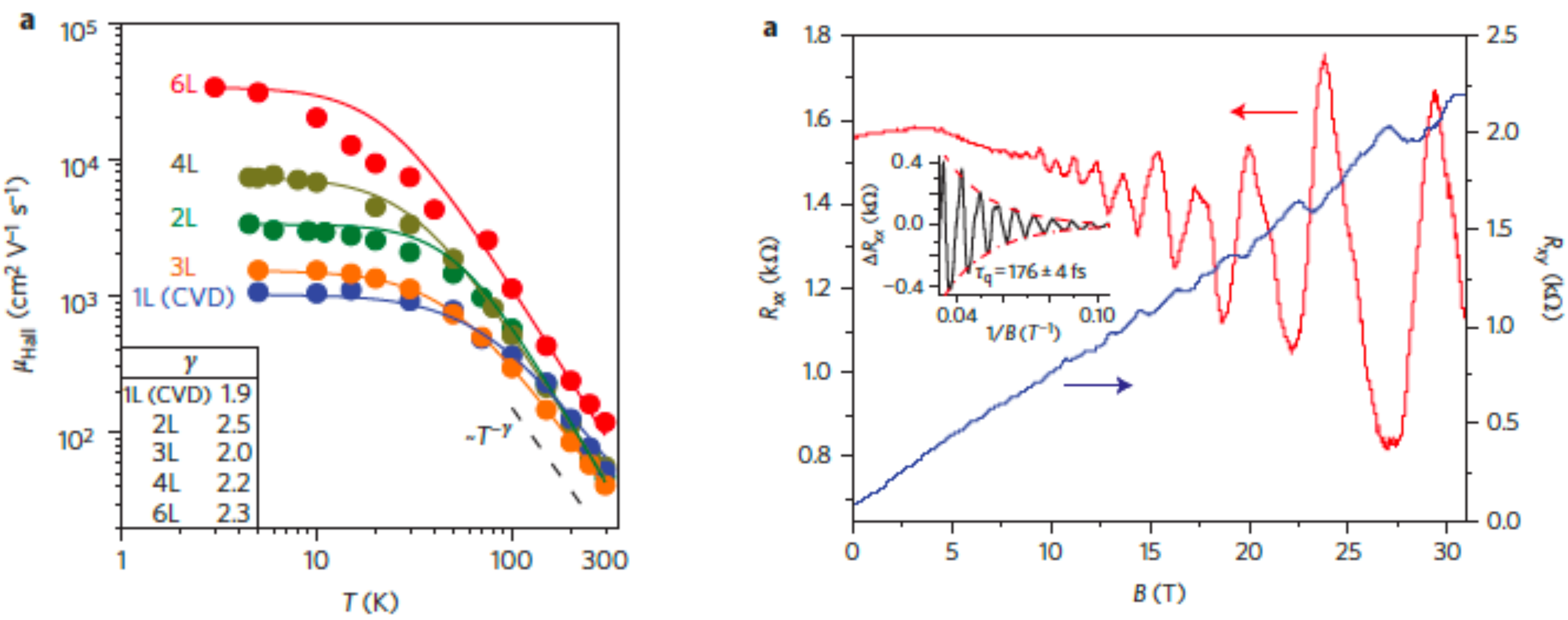

X. Cui et al., Nature Nano. 10, 534 (2015)

Final summary

New materials for new electronic devices

2D materials are an interesting playground for physics, but also engineering

Multiple device applications in electronic and opto-electronics

THE END