# *Molecular and carbon-based electronic systems*

| | |
|---|---|
| **when** | Wednesday, 12h00 |
| **where** | Seminar room 3.12, Physics Dpt, Klingelbergstrasse 82 |
| **credit** | 2KP |
| **debit** | attendance + 1 presentation |
| **VV** | lecture Nr. 37839-01 |
| **web** | **https://www.empa.ch/web/s405/mces** |

**Contact**

**Michel Calame**
*Empa & Physics Dpt., Uni Basel*
***michel.calame@empa.ch****, michel.calame@unibas.ch*

**Vorlesung Uni Basel, FS2025**

# Topics & Presentations

**Timeline**

- 19.03.2025 **Papers selection**
  - AC Fullerene-Based Single Molecule Diodes with Huge Rectification Ratios (2025) https://doi.org/10.1039/D4TC04233F
  - TLA Robust chemical analysis with graphene chemosensors and machine learning (2024) https://doi.org/10.1038/s41586-024-08003-w
  - AYY Biosensor Chip for Point-of-Care Diagnostics: Carbon Nanotube Sensing Platform for Bacterial Detection and Identification (2024) https://doi.org/10.1109/TNANO.2024.3380997

# Topics & Presentations

**Timeline**

- 19.03.2025 Papers selection

- **16.04.2025** **V1 Presentation to MC**
  feedback on 23.04

- **21.05.2025** **Final presentation to MC**

- 28.05.2025 Presentations by students

# Presentation

**Presentation (15-20 min)**

**Q&A, discussion with Audience** (5-10 min)

- Encourage questions and critical thinking
- Discuss potential implications (understanding) or applications

- Introduction (1 min)
  - Title/authors/journal/date
  - Brief overview of the topic and its importance; your motivation for choosing this topic
- Background and Context (2 min)
  - Brief literature review / timeline of related research & Goal of research
- Methods (1 min)
  - Study design (what is studied) and key experimental techniques
- **Results (6-8 min)**
  - Present main findings using figures and tables from the paper; explain the figures and the graphs
  - Highlight key data and significance
- **Discussion and Critical Analysis (3-6 min)**
  - Interpretation of results
  - Strengths and limitations of the study
- Conclusion (2 min)
  - Summary of main points; take home message
  - Outlook: open questions, future directions

# Summary

- On the importance of electronic chips

- Basic building block : the transistor

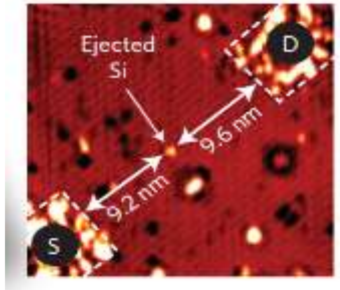
- The transistor is 75
  Science, Special section, 18 Nov. 2022

- How small can it get ?


THE WALL STREET JOURNAL.

Chips Are in Hot Demand—and That's a Problem

STM lithography
and phosphine
($PH_3$) dosing




LETTERS

PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21

nature nanotechnology

A single-atom transistor

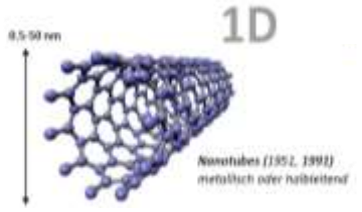
Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*

# Outline

## Electronics beyond Silicon

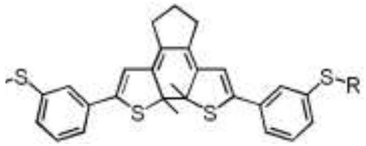
- other possible pathways for electronics

*power consumption, sustainability & life cyle, energy conversion*



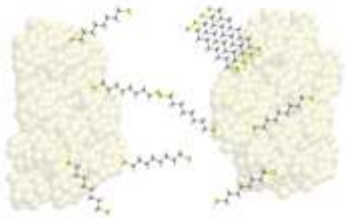
## Carbon allotropes

- discovery



## Carbon & molecular electronics

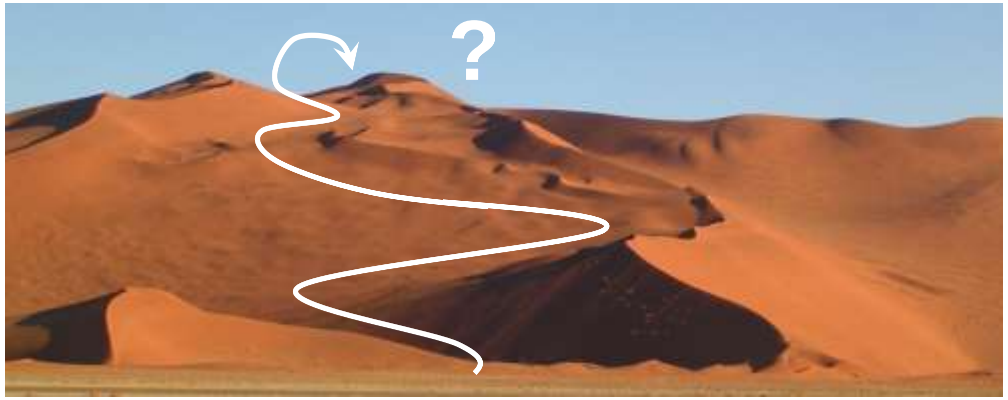
- brief historical account
- a word about computing
- why molecules



## Nanoscale junctions

- how to contact nm-scale objects

# electronics beyond Si

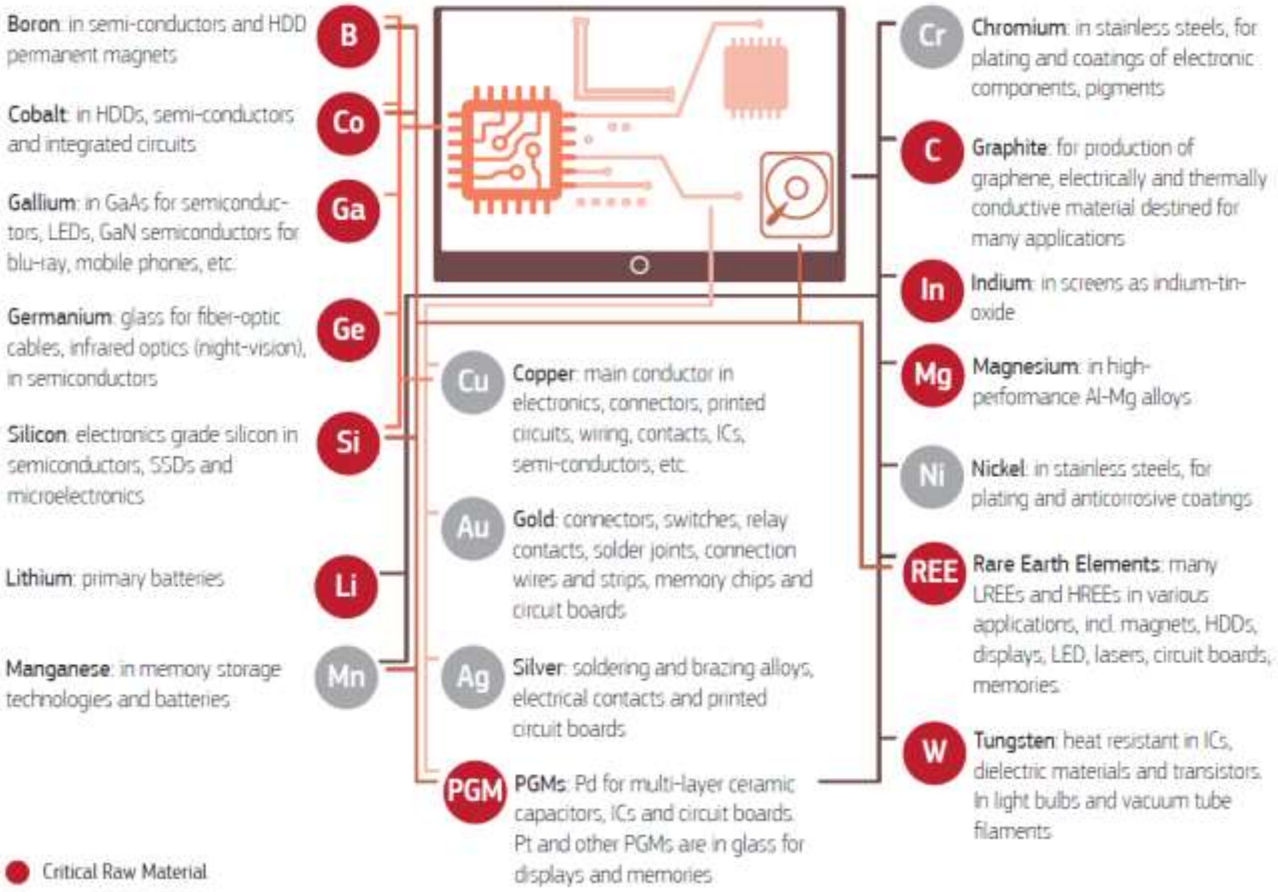


Other materials ?

# Electronics beyond Si

## Materials ressources are not infinite

Figure 44. Raw materials in digital technologies



**Boron**: in semi-conductors and HDD permanent magnets

**Cobalt**: in HDDs, semi-conductors and integrated circuits

**Gallium**: in GaAs for semiconductors, LEDs, GaN semiconductors for blu-ray, mobile phones, etc.

**Germanium**: glass for fiber-optic cables, infrared optics (night-vision), in semiconductors

**Silicon**: electronics grade silicon in semiconductors, SSDs and microelectronics

**Lithium**: primary batteries

**Manganese**: in memory storage technologies and batteries

**Copper**: main conductor in electronics, connectors, printed circuits, wiring, contacts, ICs, semi-conductors, etc.

**Gold**: connectors, switches, relay contacts, solder joints, connection wires and strips, memory chips and circuit boards

**Silver**: soldering and brazing alloys, electrical contacts and printed circuit boards

**PGMs**: Pd for multi-layer ceramic capacitors, ICs and circuit boards. Pt and other PGMs are in glass for displays and memories

**Chromium**: in stainless steels, for plating and coatings of electronic components, pigments

**Graphite**: for production of graphene, electrically and thermally conductive material destined for many applications

**Indium**: in screens as indium-tin-oxide

**Magnesium**: in high-performance Al-Mg alloys

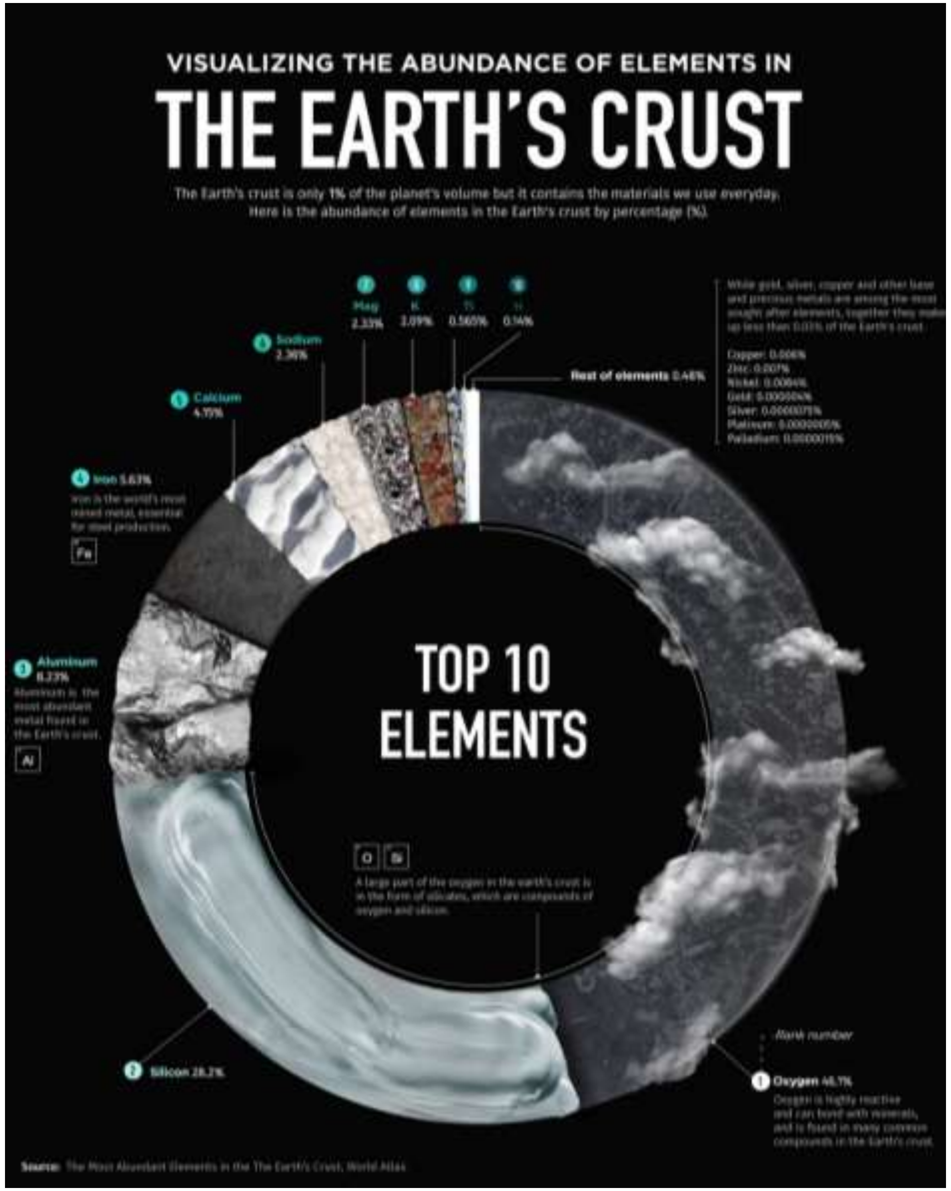
**Nickel**: in stainless steels, for plating and anticorrosive coatings

**Rare Earth Elements**: many LREEs and HREEs in various applications, incl. magnets, HDDs, displays, LED, lasers, circuit boards, memories

**Tungsten**: heat resistant in ICs, dielectric materials and transistors. In light bulbs and vacuum tube filaments

● Critical Raw Material

Source: (BCG, 2018).



Source: The Most Abundant Elements in the The Earth's Crust, World Atlas

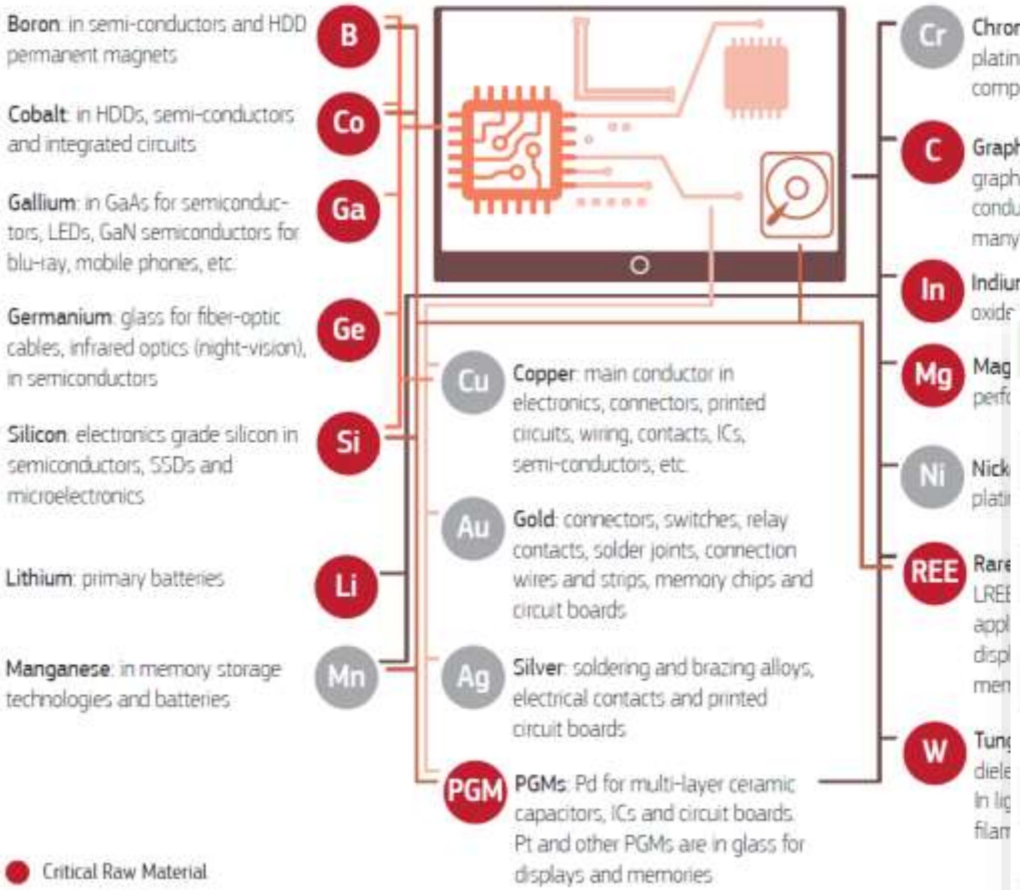
https://www.visualcapitalist.com/visualizing-the-abundance-of-elements-in-the-earths-crust/

European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020

# Electronics beyond Si

## Materials ressources are not infinite

**Figure 44.** Raw materials in digital technologies



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**Mag** perf

**Nick** plati

**Rare** LREE appl displ mem

**Tung** diele In lig filam

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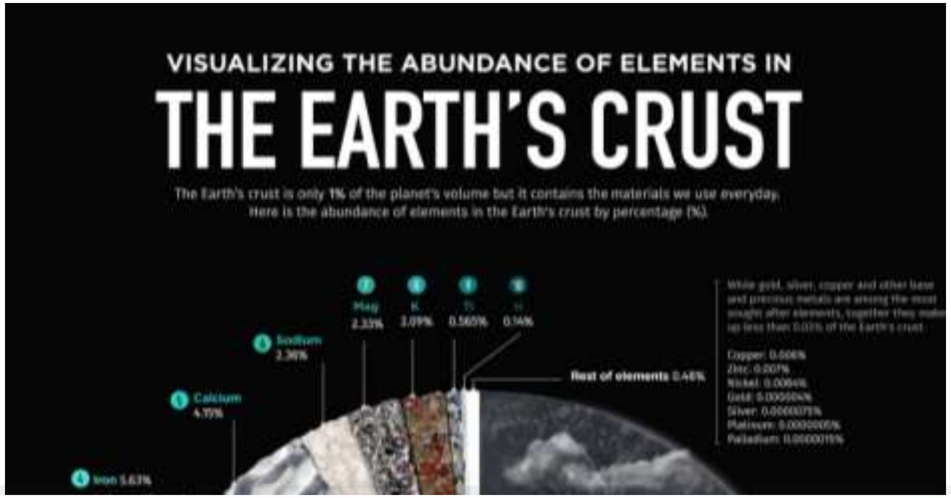
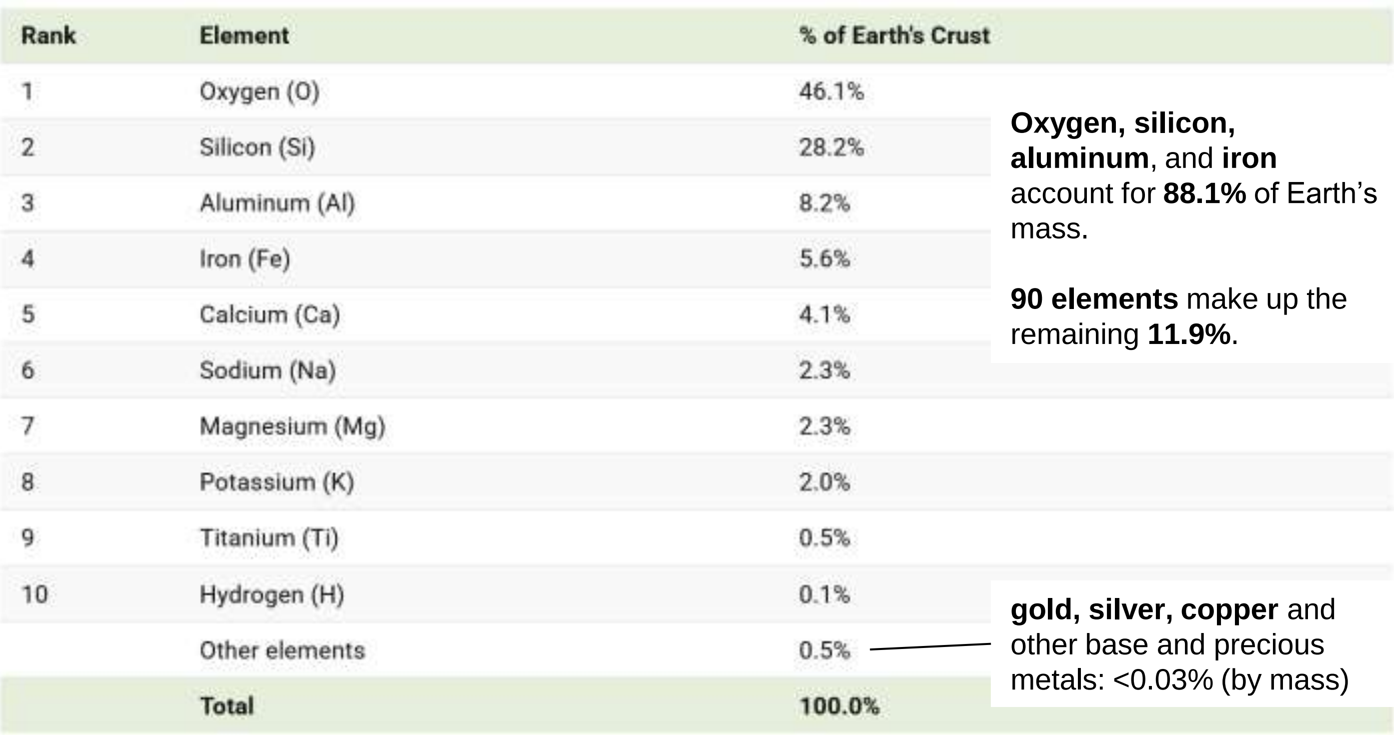




| Rank | Element | % of Earth's Crust |
|---|---|---|
| 1 | Oxygen (O) | 46.1% |
| 2 | Silicon (Si) | 28.2% |
| 3 | Aluminum (Al) | 8.2% |
| 4 | Iron (Fe) | 5.6% |
| 5 | Calcium (Ca) | 4.1% |
| 6 | Sodium (Na) | 2.3% |
| 7 | Magnesium (Mg) | 2.3% |
| 8 | Potassium (K) | 2.0% |
| 9 | Titanium (Ti) | 0.5% |
| 10 | Hydrogen (H) | 0.1% |
|  | Other elements | 0.5% |
|  | **Total** | **100.0%** |

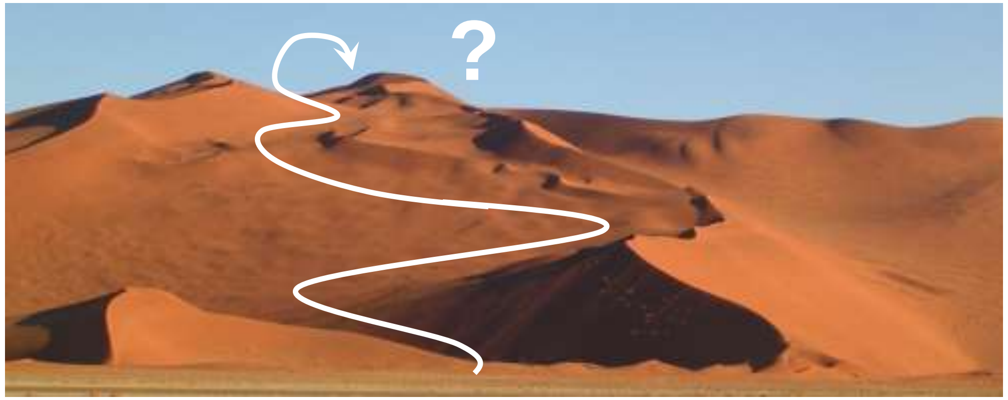
**Oxygen, silicon, aluminum**, and **iron** account for **88.1%** of Earth's mass.

**90 elements** make up the remaining **11.9%**.

**gold, silver, copper** and other base and precious metals: <0.03% (by mass)

European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020

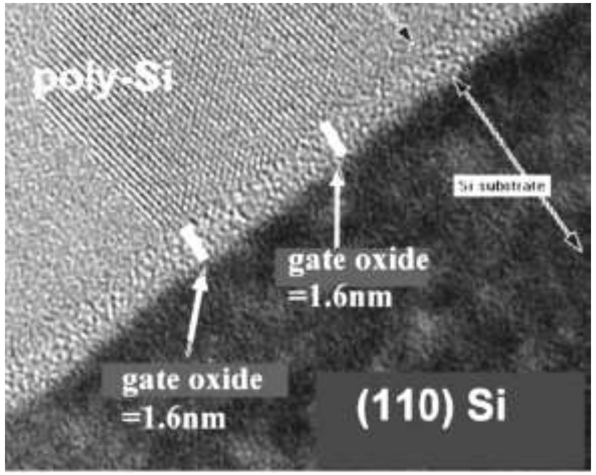
# electronics beyond Si



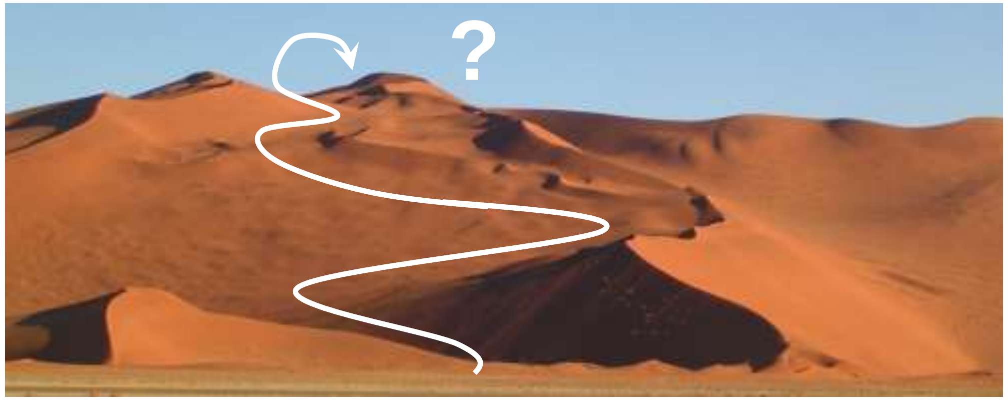
## What is the Problem with Silicon ?

Transistors "carved" out of bulk materials (Si)
⇨ surface roughness impacts mobility, band gap & leads to device to device variability (**each atom matters**!)

High density
⇨ thermal issues



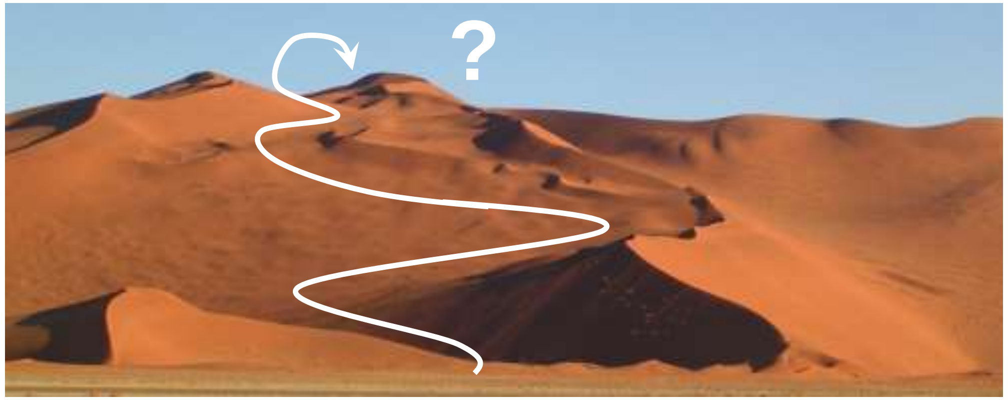
# electronics beyond Si

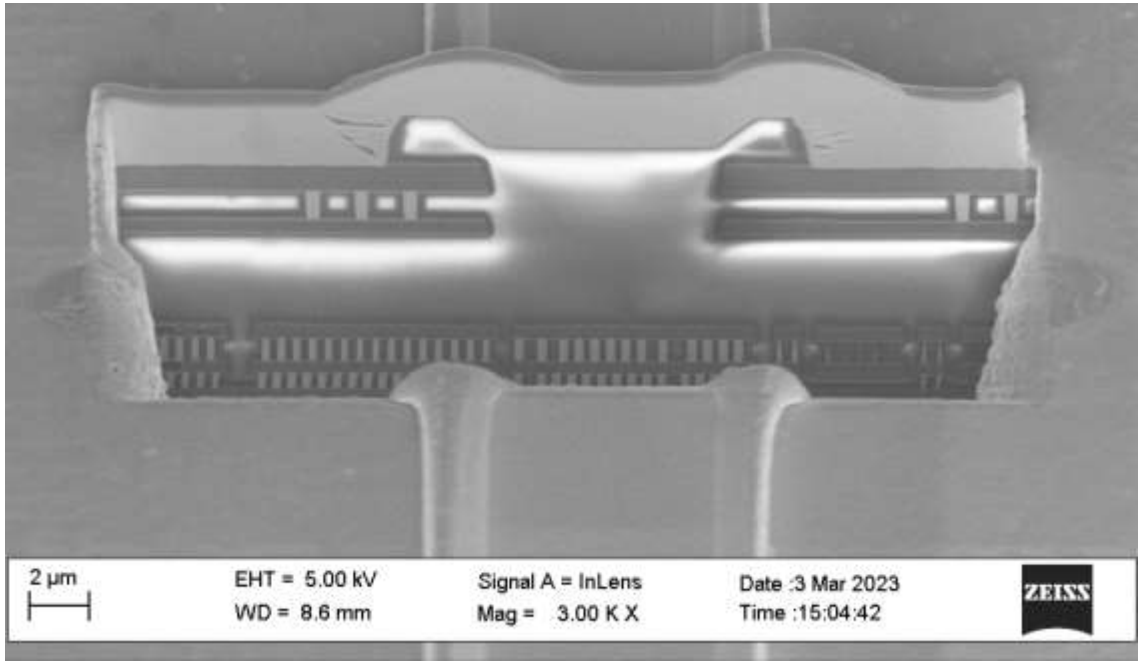


Other materials

Other architectures ?

# electronics beyond Si





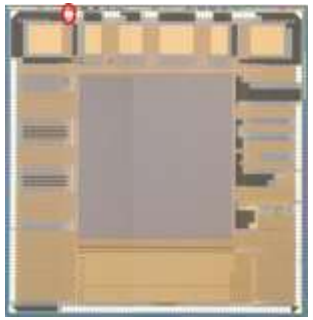
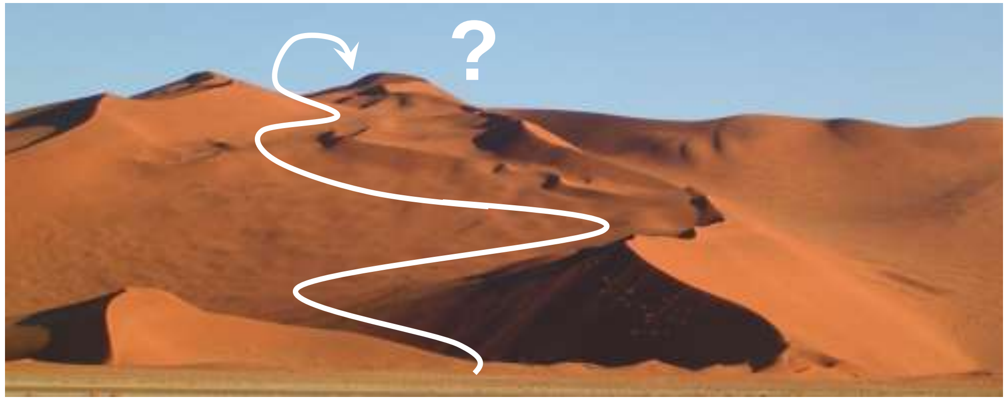


Image: E. Wu et al., Empa

**FIB cross-section and SEM image of a bonding pad in a Readout Integrated Circuit (ROIC) chip**

# electronics beyond Si



## Architectures : 3D integration, new nanosystems

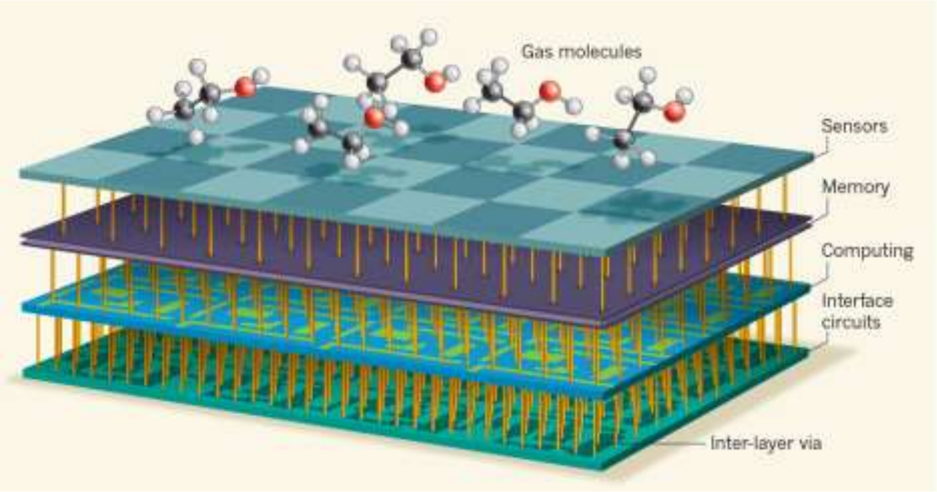
*Shulaker, Wong, Mitra et al. Nature 2017*

LETTER

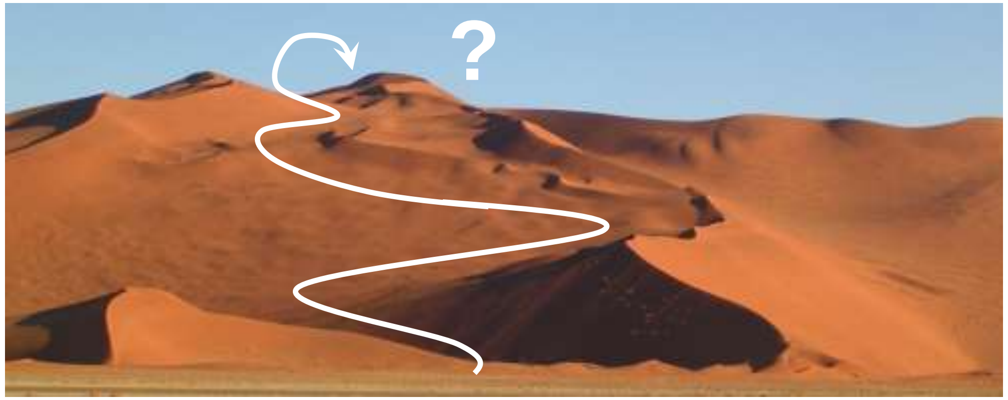
doi:10.1038/nature22994

**Three-dimensional integration of nanotechnologies for computing and data storage on a single chip**

Max M. Shulaker[1,2], Gage Hills[1], Rebecca S. Park[1], Roger T. Howe[1], Krishna Saraswat[1], H.-S. Philip Wong[1] & Subhasish Mitra[1,3]

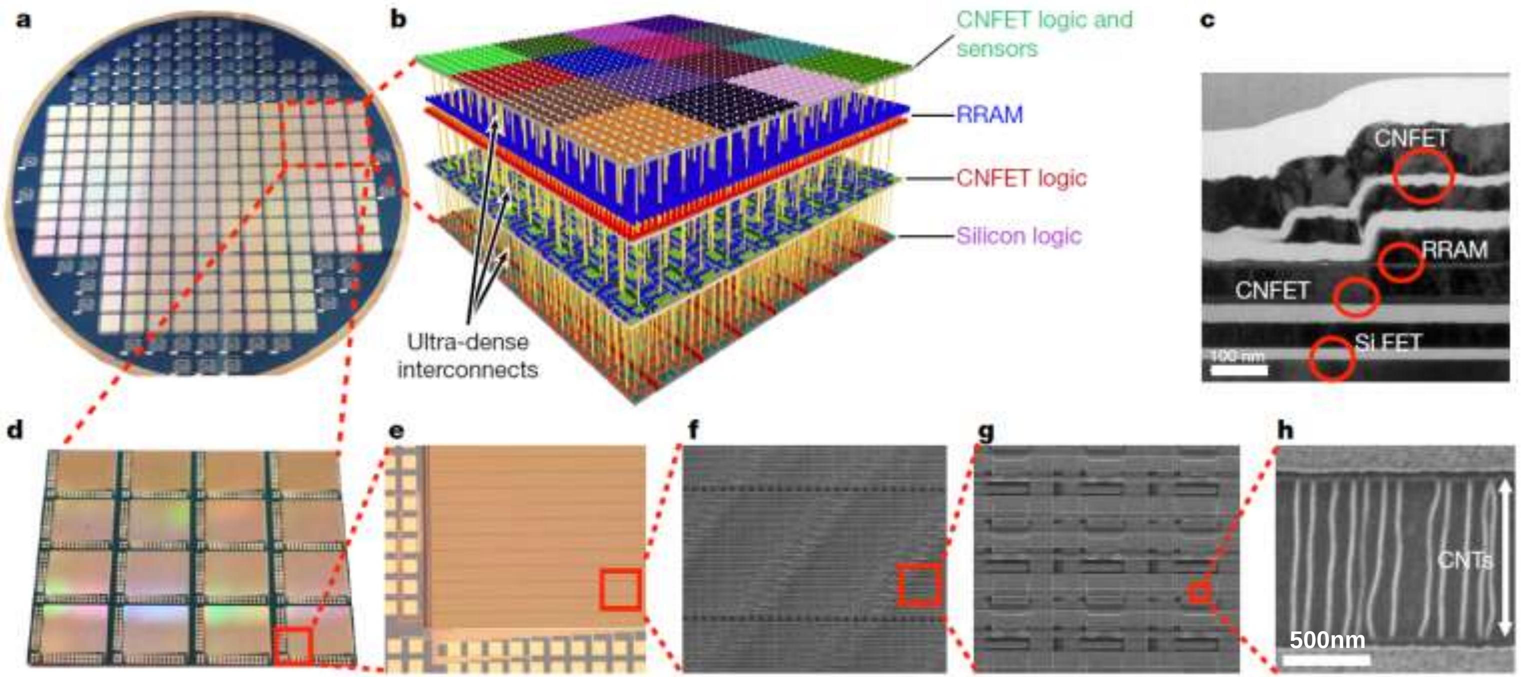


# electronics beyond Si



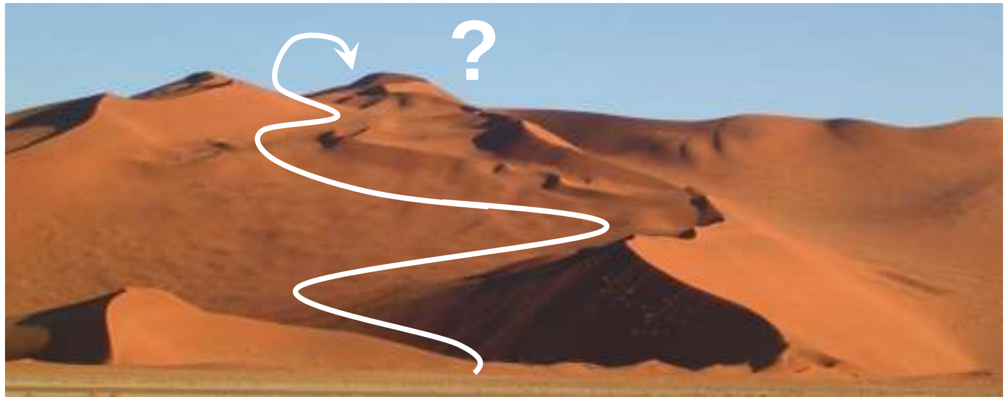
## 3D integration, novel nanosystem

*Shulaker, Wong, Mitra et al. Nature 2017*



Full chip dimensions,
1.7 cm × 2.2 cm;
scale bar, 500 mm

# electronics beyond Si



**Other materials**

AAAS 2015 ANNUAL MEETING
INNOVATIONS, INFORMATION, AND IMAGING
SAN JOSE, CA

Beyond Silicon: New Materials for 21st Century Electronics

Saturday, 14 February 2015: 8:00 AM-9:30 AM

Beyond Silicon: Carbon-Based Nanotechnology

Nathan P. Guisinger and Michael S. Arnold, Guest Editors

*MRS Bulleting 2010 special issue*

INTRODUCTION

Looking Beyond Silicon

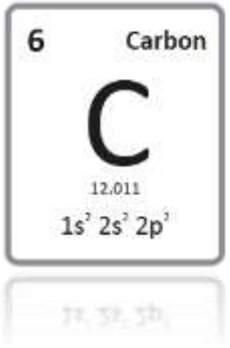
*Science 2010 special issue*

physicstoday

Industrial Physics Forum 2013: The future of electronics

What technologies will extend silicon's reign as the preeminent material for electronics? What materials will ultimately supplant silicon?
**Charles Day,** December 2013

# a quiz about best materials



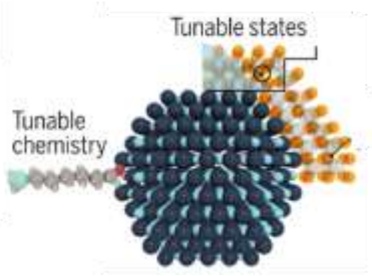
| | |
|---|---|
| Mechanical | |
| – Highest Youngs's modulus? | → Diamond |
| – Highest tensile strength? | → Graphene |
| – Hardest? | → Diamond |
| Thermal | |
| – Best heat conductor? | → Diamond, graphene |
| – Highest melting point? | → Tantalum hafnium carbide, graphene |
| Best electric conductor? | |
| – Highest current density | → Carbon nanotubes |
| – Low resistivity? | → Graphene |
| – Highest electron mobility | → Two-dimensional electron gas in semiconductor heterostructure at cryogenic temperature, graphene at room temperature |

M. Perrin

# low D(imensional) Materials

**Small Molecules &**
**Synthetic**
**Quantum Dots**

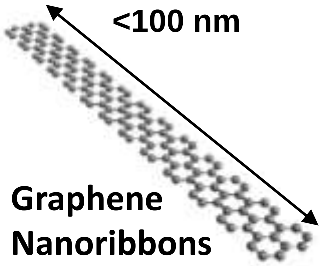
## 0D

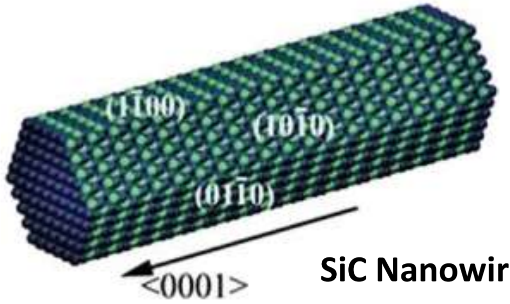


de Arquer *et al.* Science (2021)

## 1D

**Nanowires, Nanoribbons**

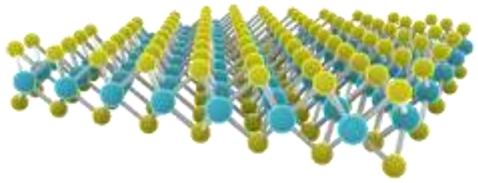




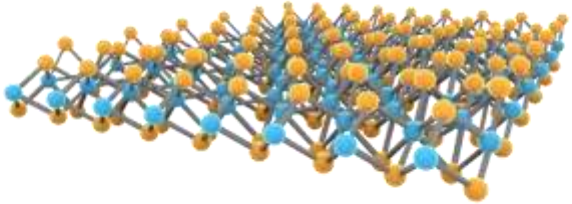
**SiC Nanowire**

## 2D

**E.g.: Transition Metal Dicalchogenides**

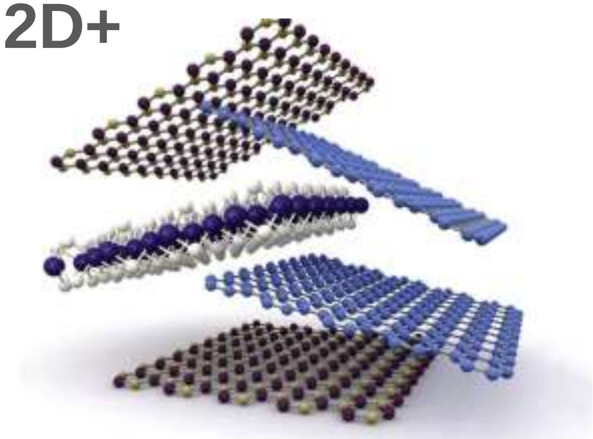


Molybdenum disulphide ($MoS_2$)



Tungsten ditelluride ($WTe_2$)

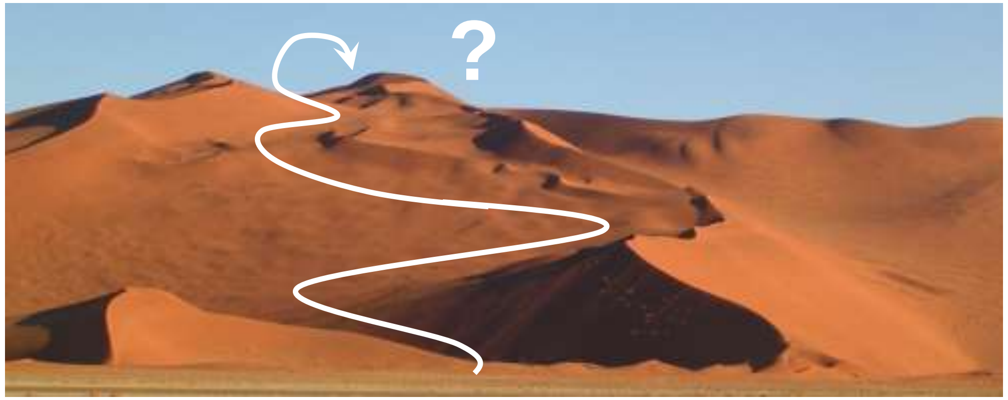
## 2D+



Novoselov *et al.* Science (2016)

**Heterogeneous Integration**
*with/without lattice mismatch*

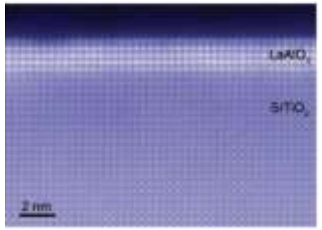
# electronics beyond Si



## Materials…

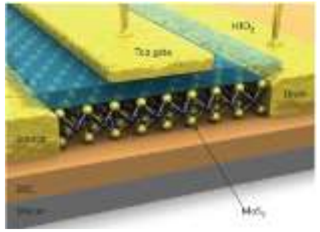
**Transition metal oxides**
charge, spin, orbital degrees of freedom for diversity of phases exploiting e-e correlation (e.g.: $TiO_2$, perovskites $ABO_3$ )

**Oxides interfaces**
LaAlO3-SrTiO3 heterostructures

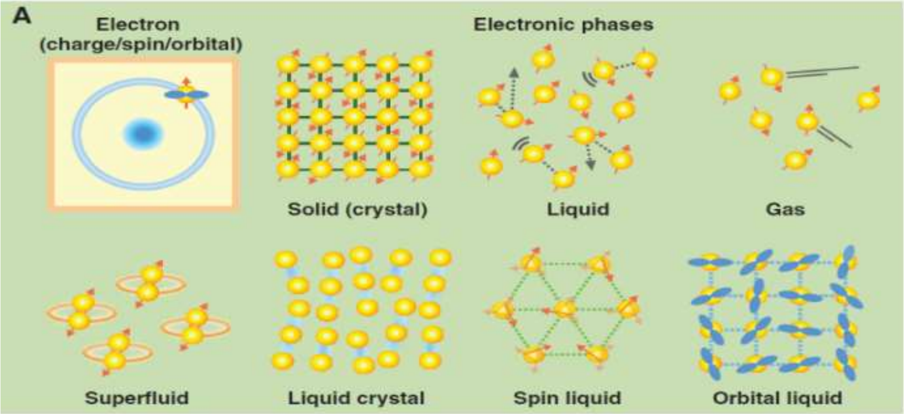


*Mannhardt et al., Science 2013*

**Transition metal dichalcogenides ("Native" 2D)**
$MoS_2$, $WS_2$, …



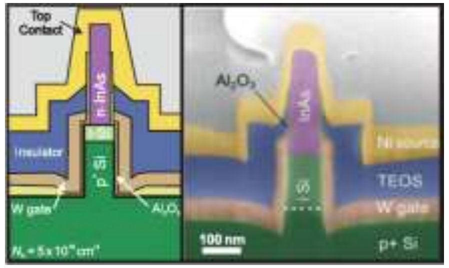
*Strano et al., Nat. Nano 2012*



*Takagi et al., Science 2013*

**III–V compound semic. transistors**

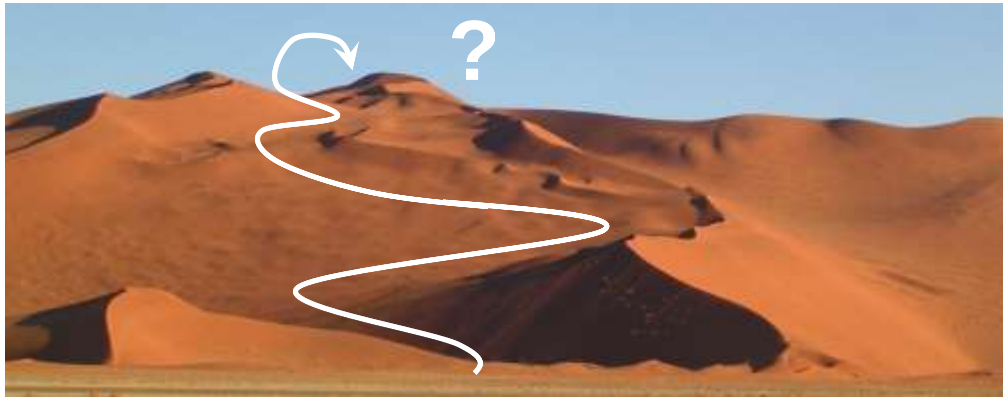
*NW tunnel FETs*
*Riel et al., MRS Bulletin 2014*



## … and transport regimes

diffusive, ballistic, tunneling, hydrodynamic
*control of e-e, e-ph, e-defect interactions*

# electronics beyond Si



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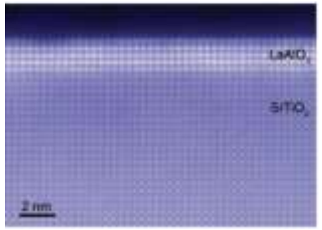

*Mannhardt et al., Science 2013*

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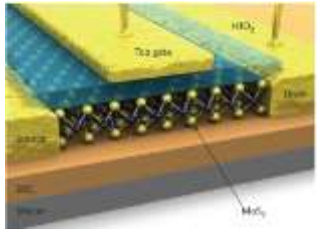

*Strano et al., Nat. Nano 2012*

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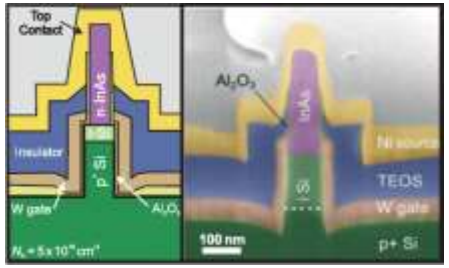
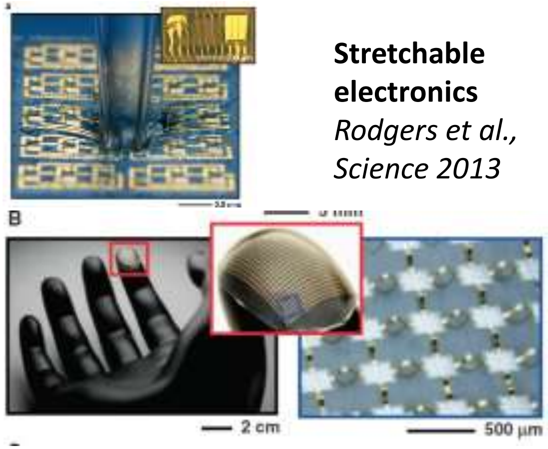


**Organic & inorganic materials with elastomeric substrates**



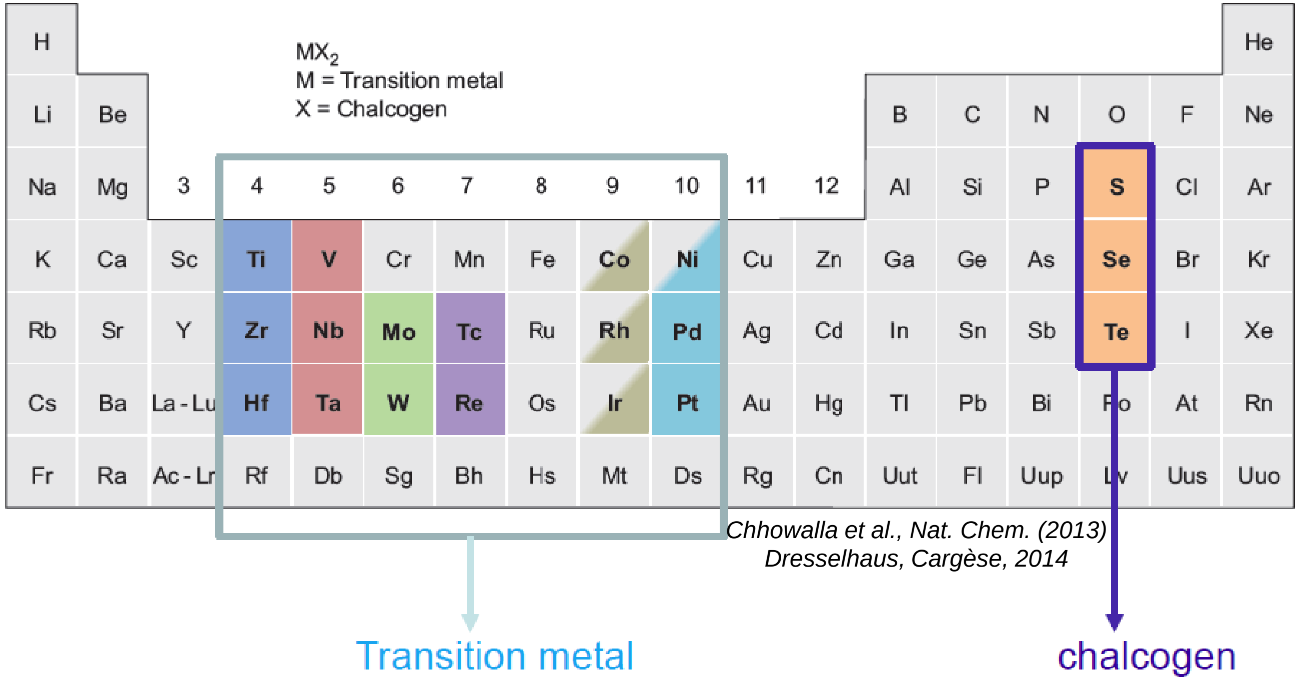
**Stretchable electronics**
*Rodgers et al., Science 2013*

# Thousands (?) of 2D Materials

## Structural and Chemical Diversity beyond graphene

**2D**

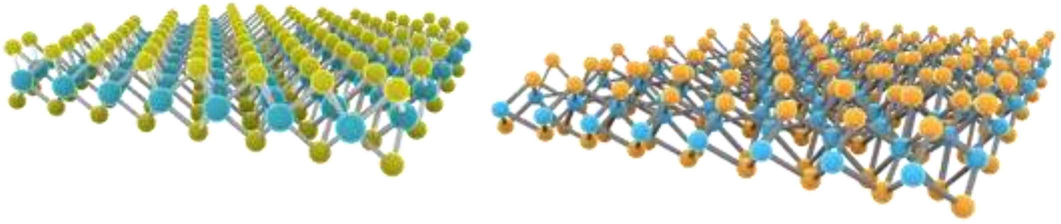
### E.g.: Transition Metal Dicalchogenides



$MX_2$
M = Transition metal
X = Chalcogen

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Al | Si | P | **S** | Cl | Ar |
| K | Ca | Sc | **Ti** | **V** | Cr | Mn | Fe | **Co** | **Ni** | Cu | Zn | Ga | Ge | As | **Se** | Br | Kr |
| Rb | Sr | Y | **Zr** | **Nb** | **Mo** | **Tc** | Ru | **Rh** | **Pd** | Ag | Cd | In | Sn | Sb | **Te** | I | Xe |
| Cs | Ba | La - Lu | **Hf** | **Ta** | **W** | **Re** | Os | **Ir** | **Pt** | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| Fr | Ra | Ac - Lr | Rf | Db | Sg | Bh | Hs | Mt | Ds | Rg | Cn | Uut | Fl | Uup | Lv | Uus | Uuo |

*Chhowalla et al., Nat. Chem. (2013)*
*Dresselhaus, Cargèse, 2014*



Molybdenum disulphide ($MoS_2$)

Tungsten ditelluride ($WTe_2$)

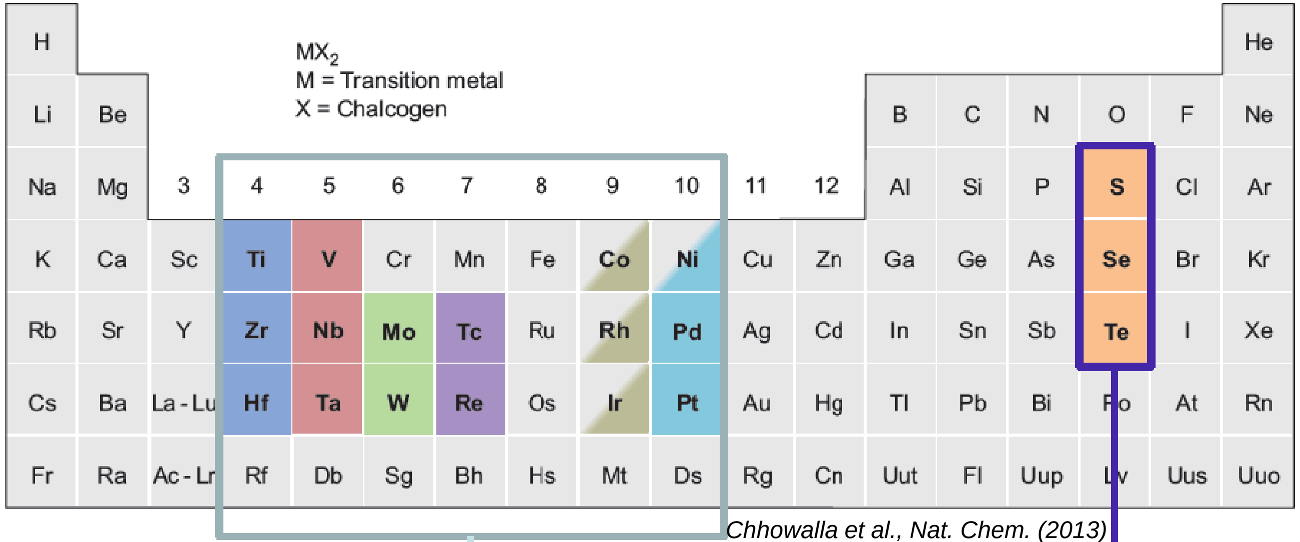
- **Structure** first determined **by Linus Pauling in 1923**
- By the late **1960s, around 60 TMDCs** were known, **at least 40 of them with a layered structure**.
- First reports on the use of **adhesive tapes** for **producing ultrathin MoS2 layers, by Robert Frindt in 1963**
- Production of **monolayer MoS2 suspensions** was first achieved **in 1986.**

*See e.g. A. Kis et al., Nat. Rev. Materials (2017)*

# Thousands (?) of 2D Materials

## Structural and Chemical Diversity

**E.g.: Transition Metal Dicalchogenides**



$MX_2$
M = Transition metal
X = Chalcogen

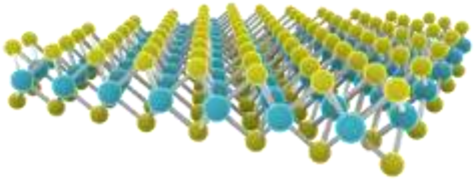
| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Al | Si | P | **S** | Cl | Ar |
| K | Ca | Sc | **Ti** | **V** | Cr | Mn | Fe | **Co** | **Ni** | Cu | Zn | Ga | Ge | As | **Se** | Br | Kr |
| Rb | Sr | Y | **Zr** | **Nb** | **Mo** | **Tc** | Ru | **Rh** | **Pd** | Ag | Cd | In | Sn | Sb | **Te** | I | Xe |
| Cs | Ba | La - Lu | **Hf** | **Ta** | **W** | **Re** | Os | **Ir** | **Pt** | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| Fr | Ra | Ac - Lr | Rf | Db | Sg | Bh | Hs | Mt | Ds | Rg | Cn | Uut | Fl | Uup | Lv | Uus | Uuo |

*Chhowalla et al., Nat. Chem. (2013)*
*Dresselhaus, Cargèse, 2014*

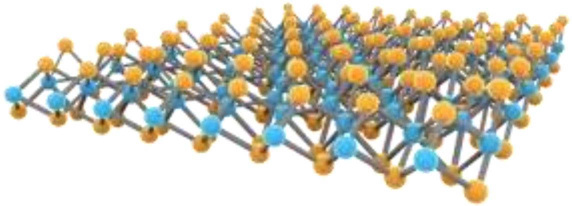
Transition metal

chalcogen

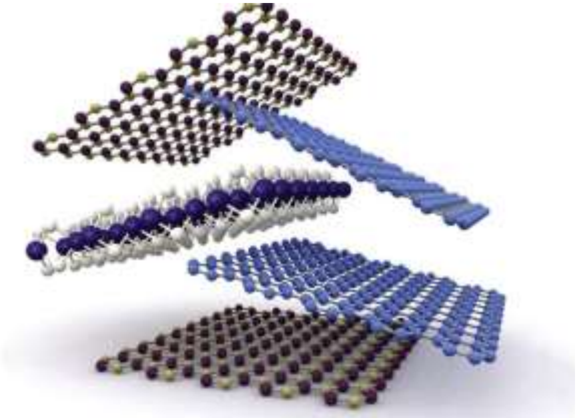
# 2D and 2D+



Molybdenum disulphide ($MoS_2$)



Tungsten ditelluride ($WTe_2$)

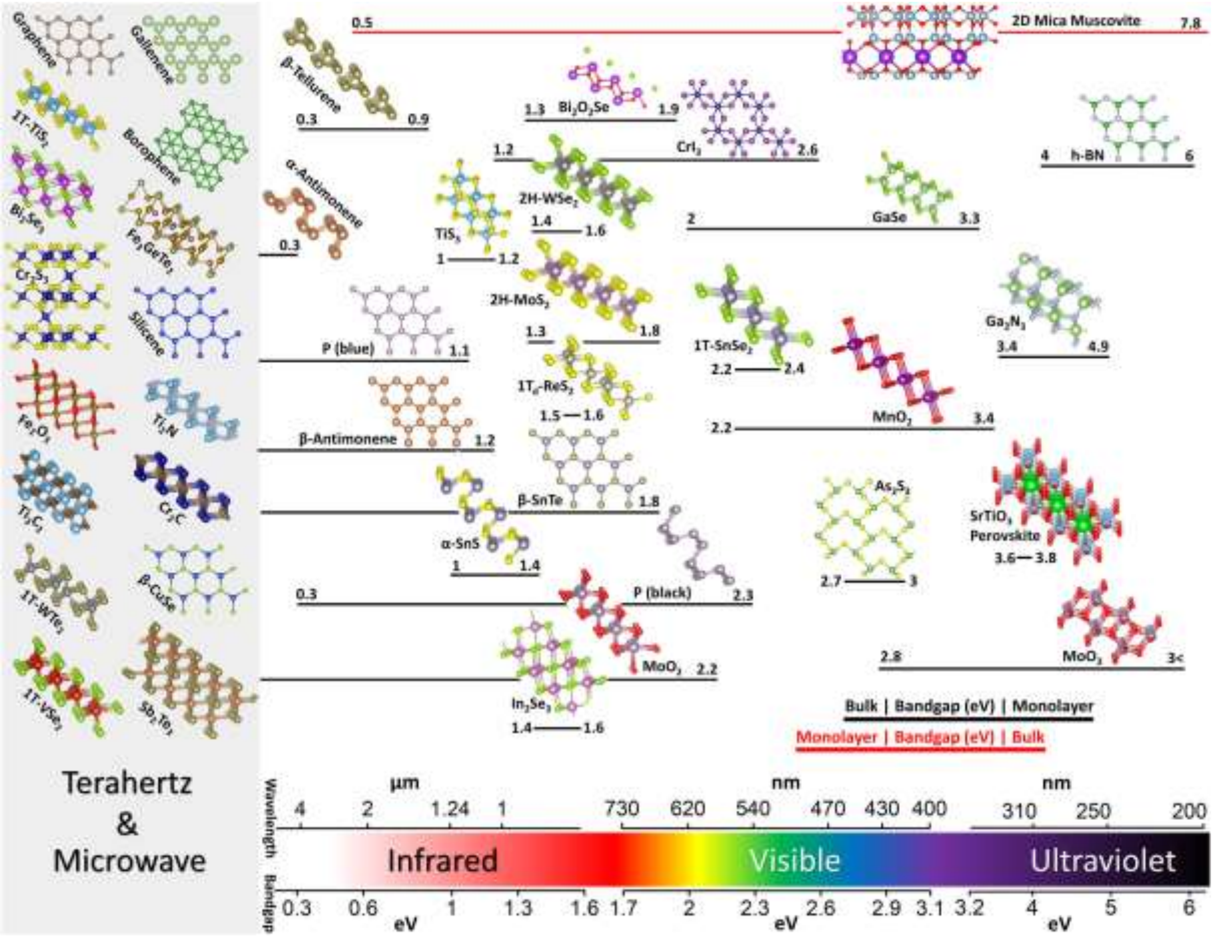


Novoselov *et al.* Science (2016)

**Heterogeneous Integration**
*with/without lattice mismatch*

# Thousands (?) of 2D Materials & **Opportunities**

## Structural and Chemical Diversity



Zero or near-zero bandgap, metallic, or semimetallic

Selected family of 2D materials and their bandgaps

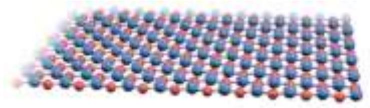
Chaves et al., npj 2D Materials (2022)

## Richness of Properties

*Sometimes no bulk analogue*

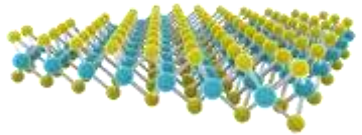
**Insulating**

hexagonal Boron Nitride
(~5.9eV)



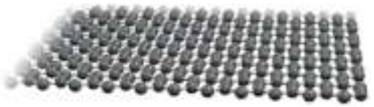
**Semiconducting**

Molybdenum Disufide
(1.8-2.7eV)



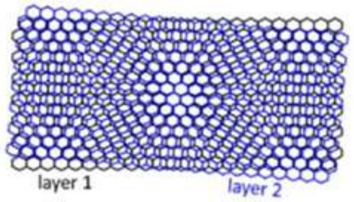
**Metallic**

Graphene



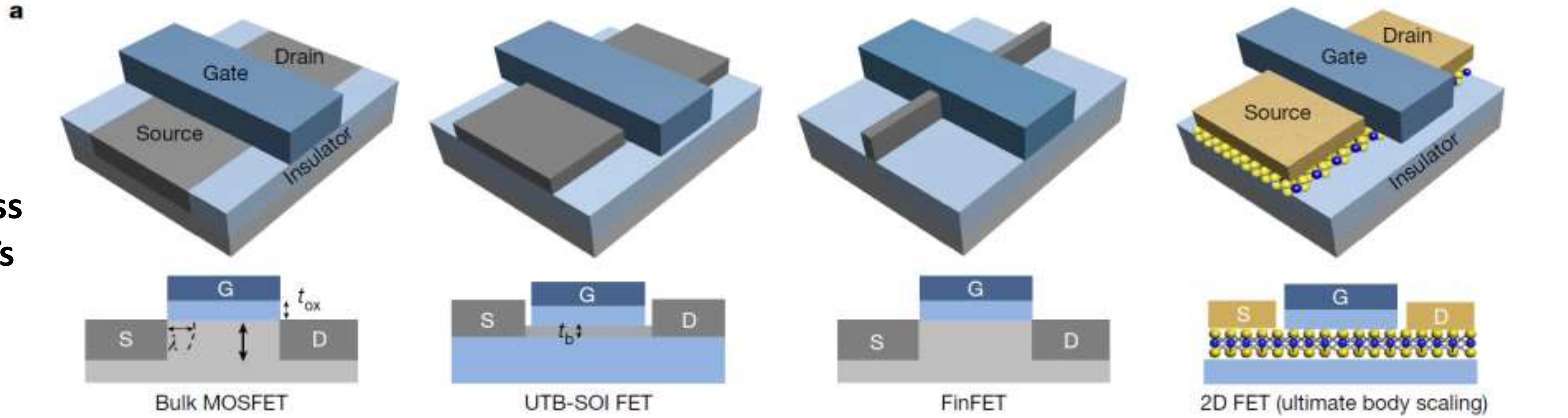
**Superconducting**

Twisted bilayer Graphene
"Magic Angle"



# Electronics beyond Si: **emergence of 2D transistors, selected properties**

**Body thickness scaling in FETs**



Bulk MOSFET

UTB-SOI FET

FinFET

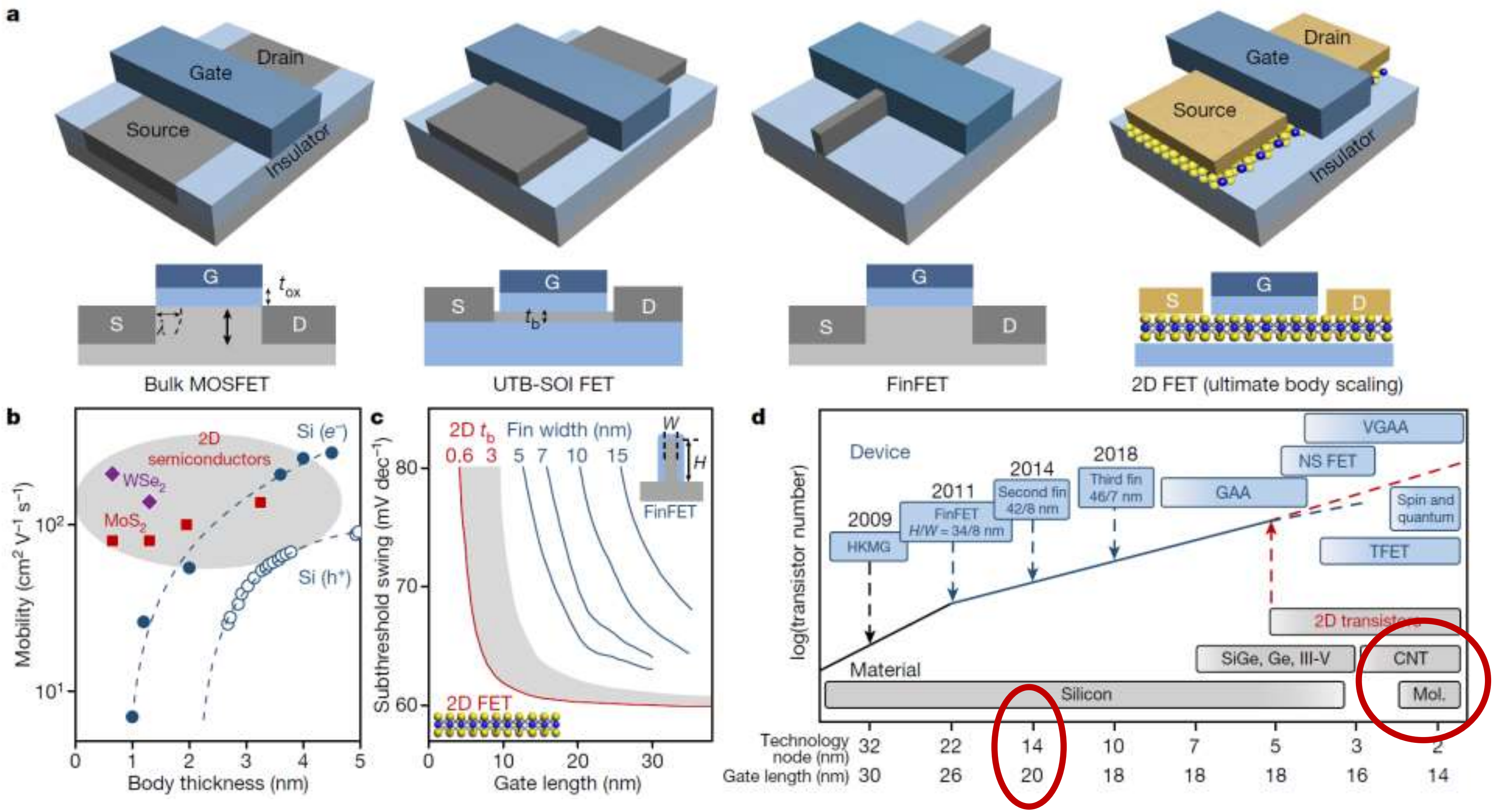
2D FET (ultimate body scaling)

ultrathin-body silicon-on-insulator

Light grey, dark grey, light blue and dark blue represent the bulk semiconductor, doped contact region, oxide and gate electrode, respectively. S, source; D, drain; G, gate

*Duan et al., Nature (2021)*

# Electronics beyond Si: **emergence of 2D transistors, selected properties**



Light grey, dark grey, light blue and dark blue represent the bulk semiconductor, doped contact region, oxide and gate electrode, respectively. S, source; D, drain; G, gate

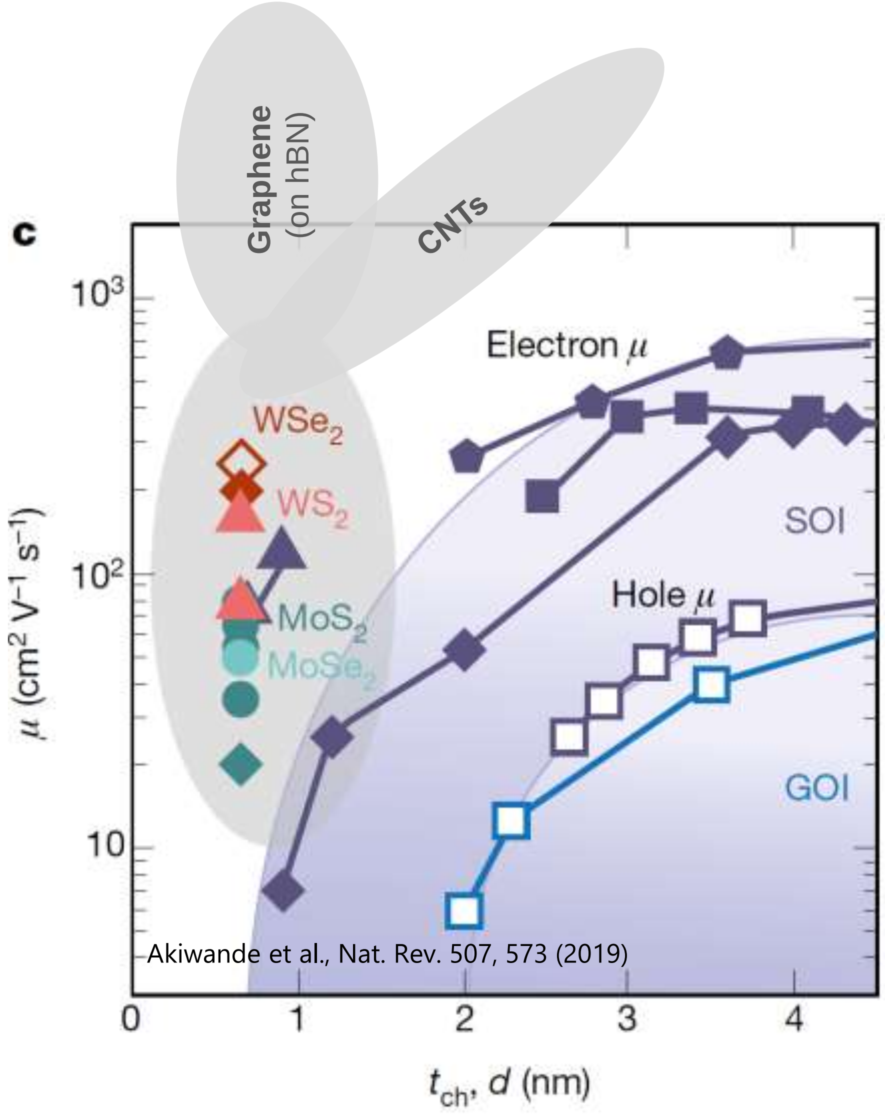
HKMG, high-*κ* dielectric and metal gate; NS FET, nano-sheet FET; CNT, carbon nanotube; Mol., molecules

*Duan et al., Nature (2021)*

# electronics beyond Si: **emergence of 2D transistors**

Atomically-thin and -precise materials

**Charge carier mobility**



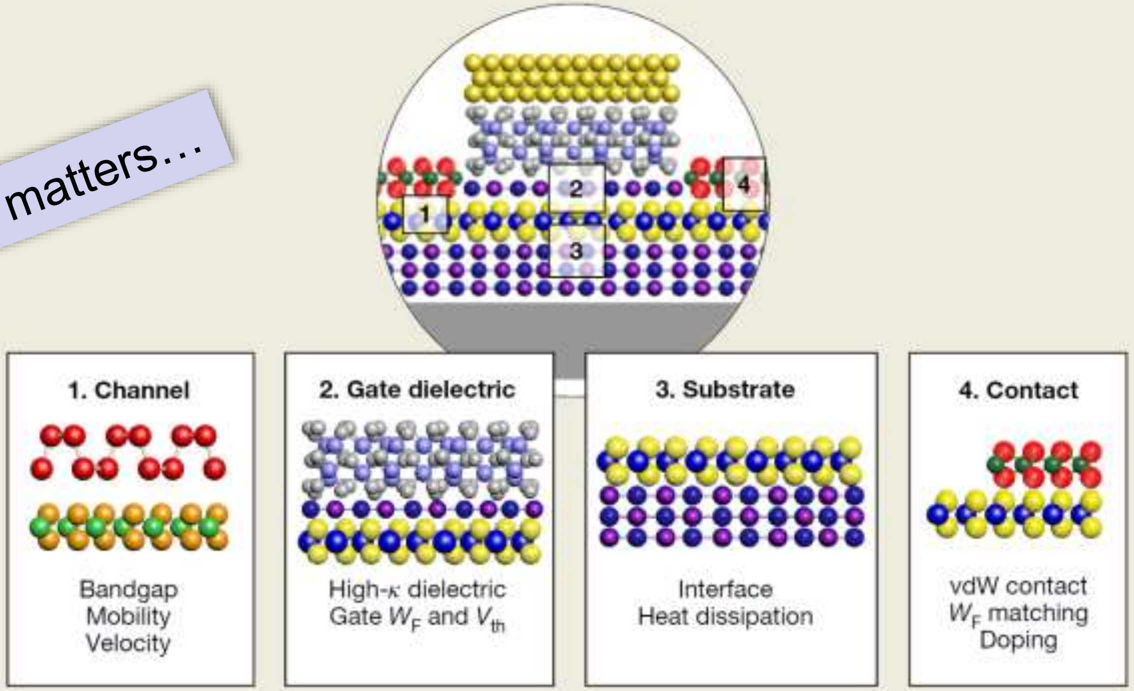
Akiwande et al., Nat. Rev. 507, 573 (2019)

# electronics beyond Si: emergence of 2D transistors

## Pathway for pushing the performance limit of 2D transistors

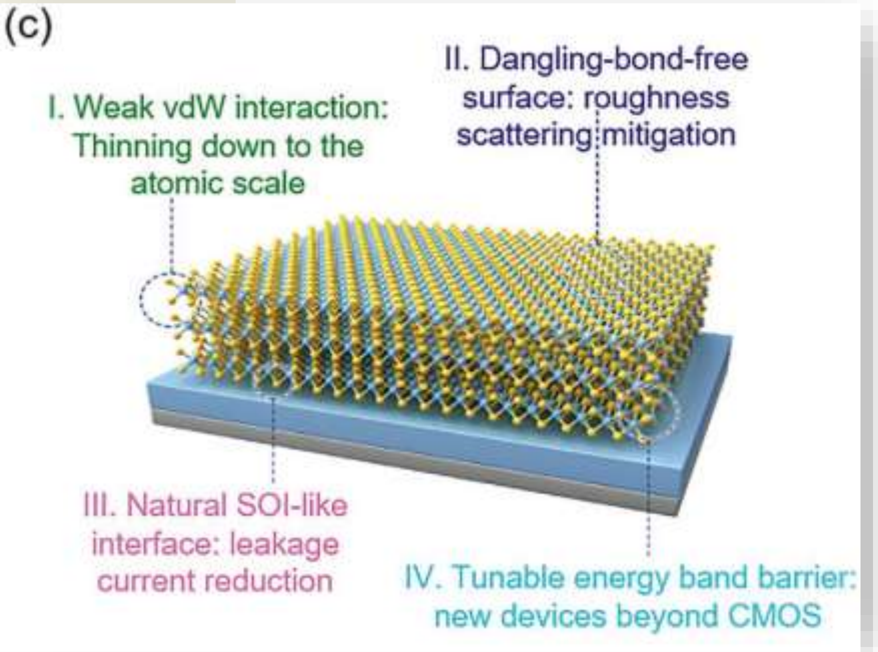
In an idealized 2D transistor, a high-mobility 2D semiconductor (monolayer or bilayer) with a desired bandgap and high $v_{sat}$ is used as the channel material with low channel resistance; an ultrathin 2D metal with the appropriate work function is used as a pinning-free vdW contact with minimized $R_c$; a high-$\kappa$ dielectric with ultrasmall equivalent oxide thickness is used as the dielectric layer to maximize the transconductance; a metal gate with designed work function is used to control the threshold voltage; and an ultrasmooth, high-thermal-conductance substrate (for example, BN) may be used for effective heat dissipation. Additionally, a monolayer BN may be used as a protection layer and interfacial layer for high-$\kappa$ dielectric integration to reduce the integration-induced structural damage and the associated interface states, and provide an additional heat-releasing pathway. The atomically clean 2D/BN vdW heterojunction at the dielectric–2D semiconductor and substrate/2D semiconductor interfaces could also minimize the interfacial trapping states and prevent undesired substrate scattering effects, thus further boosting $I_{on}$.

Each atom matters…



**Box 1 Figure | Schematic of an idealized 2D transistor showing the ultimate potential of 2D semiconductors.** $W_F$, work function; $V_{th}$, threshold voltage.

*Duan et al., Nature (2021)*

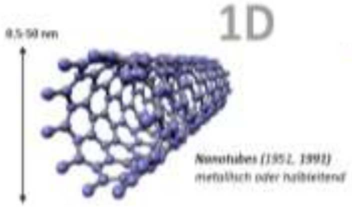


*Wang et al., Adv. Mat. (2022)*

# outline

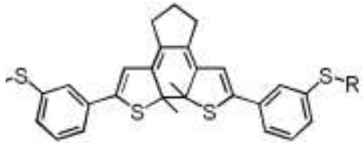
## Electronics beyond Silicon

- other possible pathways for electronics



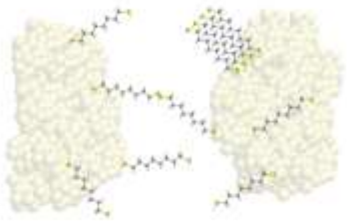
## Carbon allotropes

- discovery



## Carbon & molecular electronics

- brief historical account
- a word about computing
- why molecules



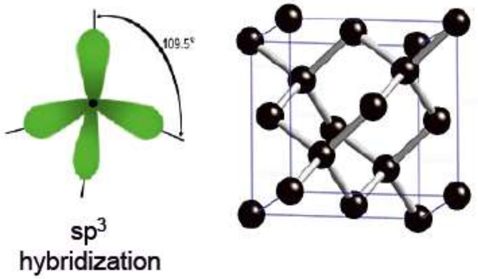
## Molecular junctions

- how to contact nm-scale objects

# Carbon and its allotropes

**3D**

***Diamant (sp$^3$ Carbon)***
- *das härteste Material*
- *sehr guter Isolator, trotzdem aber exzellenter Wärmeleiter*



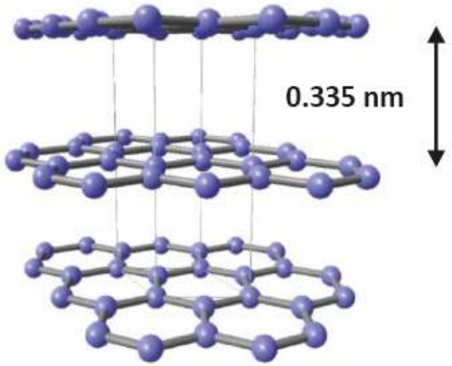
6 Carbon

C

12.011

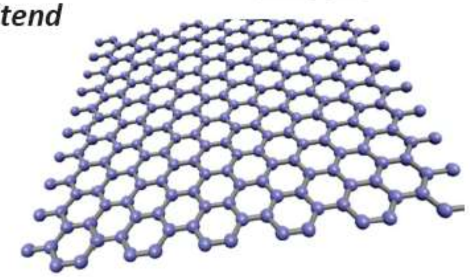
$1s^2\,2s^2\,2p^2$

***Graphit (sp$^2$ Carbon)***
- *lässt sich leicht abtragen (Bleistift)*
- *recht guter elektrischer Leiter*

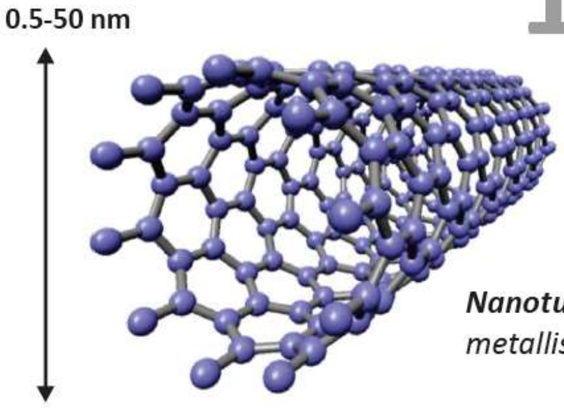


***Graphene (2004)***
***"zwischen" metallisch und halbleitend***

**2D**



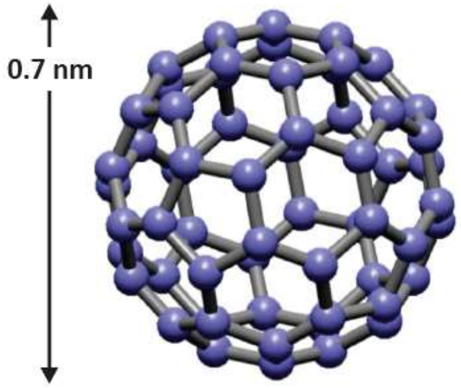
**1D**



***Nanotubes** (1951, **1991)***
*metallisch oder halbleitend*

***Fullerene $C_{60}$ (1985)***

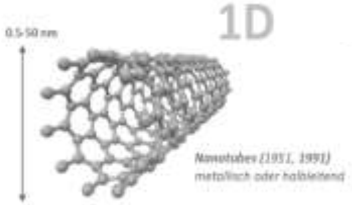
**0D**



# outline

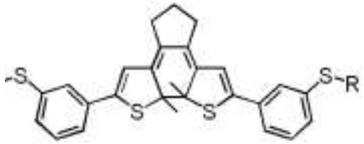
## Electronics beyond Silicon

- other possible pathways for electronics



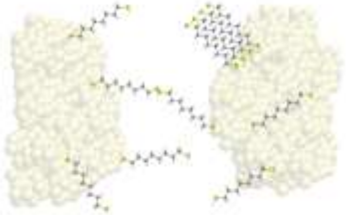
## Carbon allotropes

- discovery



## Carbon & molecular electronics

- brief historical account
- a word about computing
- why molecules

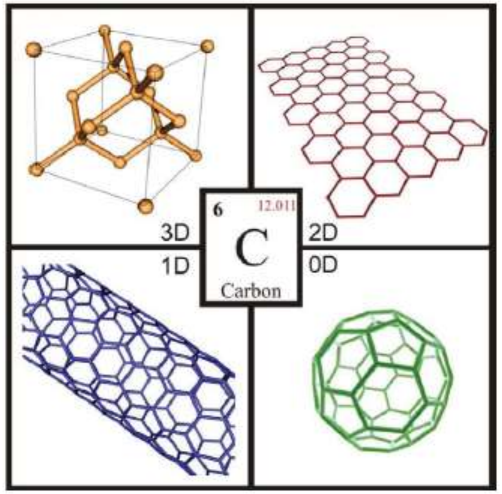


## Molecular junctions

- how to contact nm-scale objects

# carbon-based electronics

**materials**



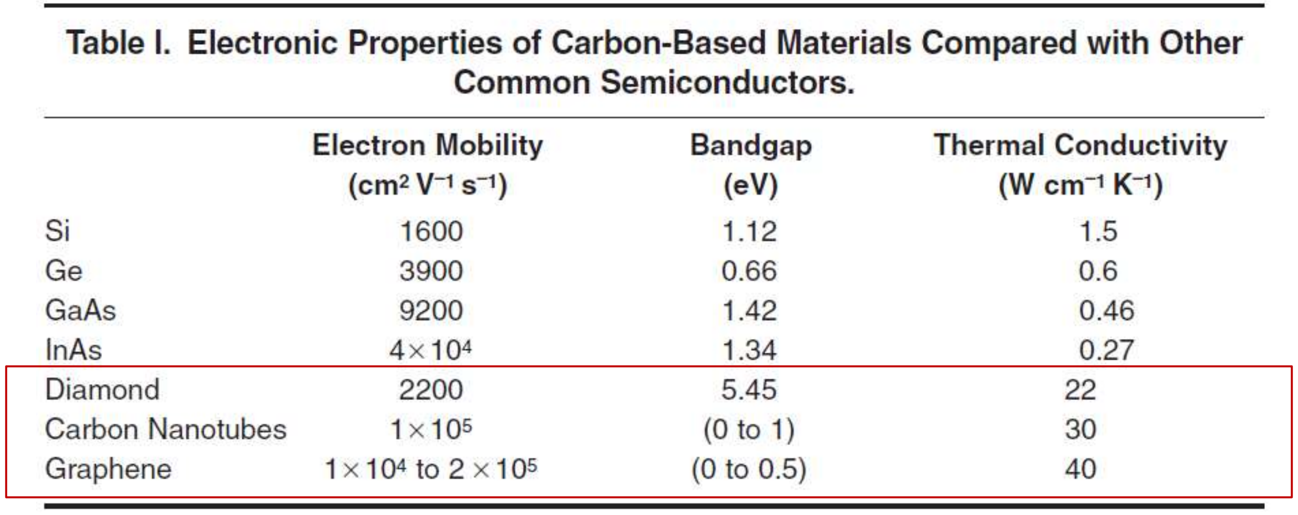


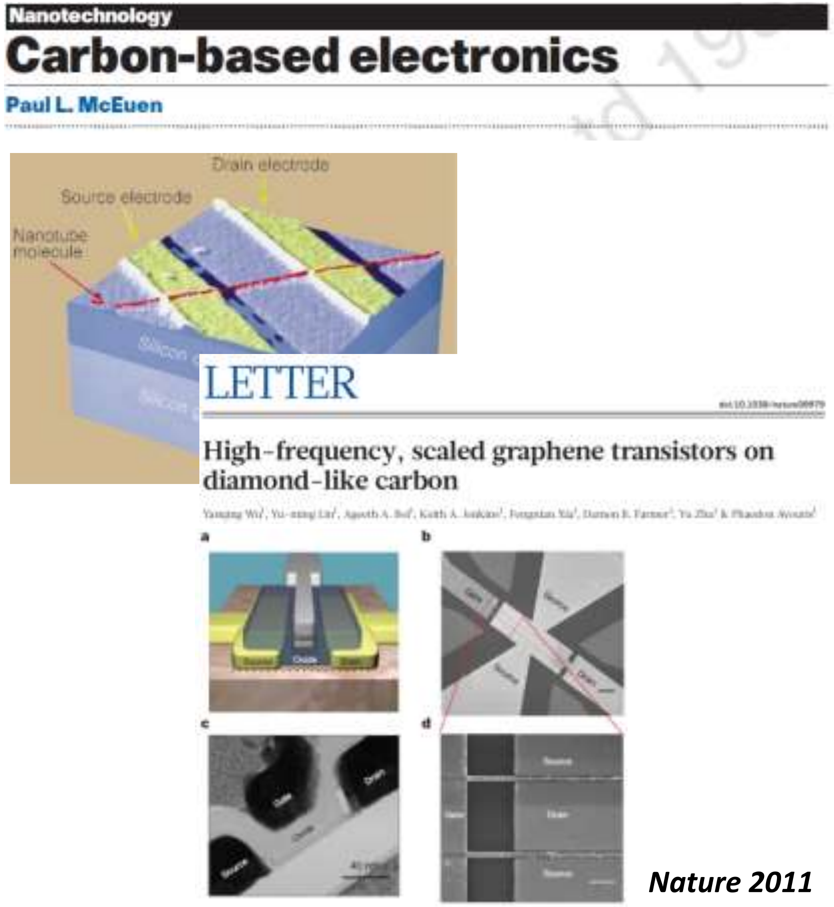
**Table I. Electronic Properties of Carbon-Based Materials Compared with Other Common Semiconductors.**

| | Electron Mobility ($cm^2 V^{-1} s^{-1}$) | Bandgap (eV) | Thermal Conductivity ($W cm^{-1} K^{-1}$) |
|---|---|---|---|
| Si | 1600 | 1.12 | 1.5 |
| Ge | 3900 | 0.66 | 0.6 |
| GaAs | 9200 | 1.42 | 0.46 |
| InAs | $4 \times 10^4$ | 1.34 | 0.27 |
| Diamond | 2200 | 5.45 | 22 |
| Carbon Nanotubes | $1 \times 10^5$ | (0 to 1) | 30 |
| Graphene | $1 \times 10^4$ to $2 \times 10^5$ | (0 to 0.5) | 40 |

*MRS Bulleting 2010 special issue*

*Overview Carbon-based electronics: see e.g. . Avouris et al. Nat. Nano 2007, McCreery, Faraday Disc. 2014*

# Carbon-based Electronics ?



**Nanotechnology**

## Carbon-based electronics

**Paul L. McEuen**

LETTER

### High-frequency, scaled graphene transistors on diamond-like carbon

***Nature 2011***

FROM THE JULY/AUGUST 2013 ISSUE

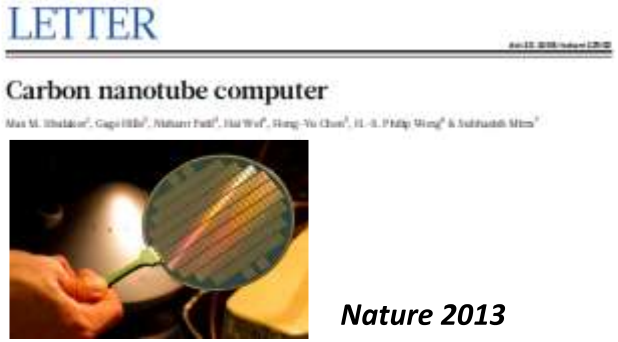
## Graphene and Nanotubes Will Replace Silicon in Tomorrow's Nano-Machines

Physicist and novelist Paul McEuen says one day nanobots will carry medicine through your bloodstream and rebuild your brain's circuitry.

By Doug Stewart | Wednesday, December 11, 2013

***Discovery magazine 2013***

*NB: novel (Spiral)*

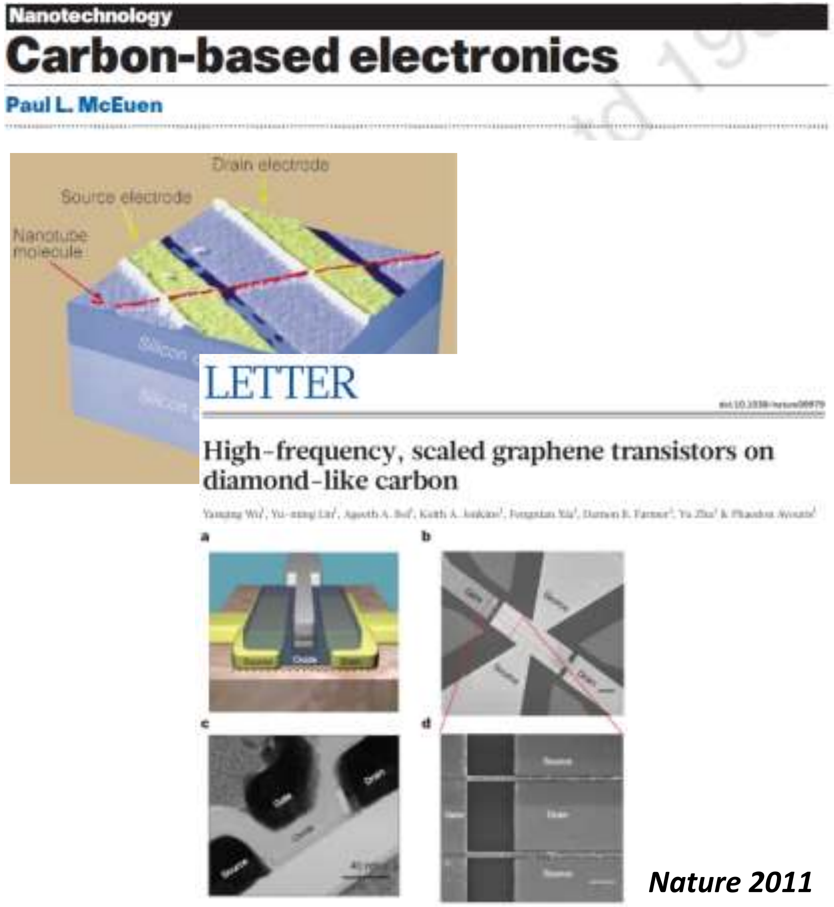


LETTER

### Carbon nanotube computer

***Nature 2013***

# Carbon-based Electronics ?



**Nanotechnology**

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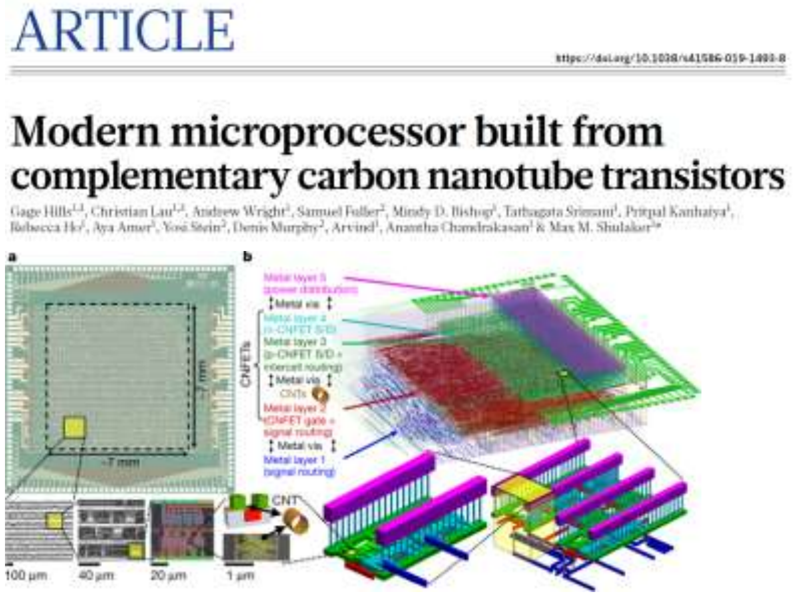
**Paul L. McEuen**

LETTER

doi:10.1038/nature09979

## High-frequency, scaled graphene transistors on diamond-like carbon

*Nature 2011*



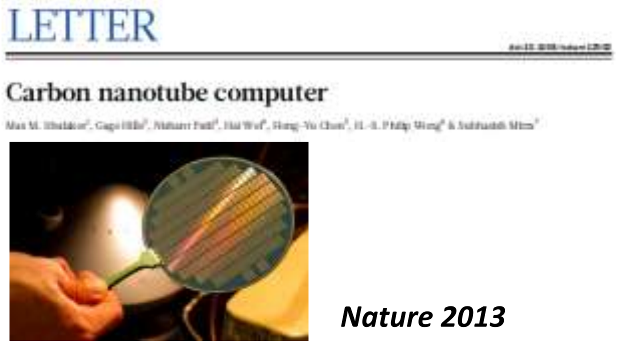
ARTICLE

https://doi.org/10.1038/s41586-019-1493-8

## Modern microprocessor built from complementary carbon nanotube transistors

Gage Hills[1,2], Christian Lau[1,2], Andrew Wright[1], Samuel Fuller[2], Mindy D. Bishop[1], Tathagata Srimani[1], Pritpal Kanhaiya[1], Rebecca Ho[1], Aya Amer[1], Yosi Stein[2], Denis Murphy[2], Arvind[1], Anantha Chandrakasan[1] & Max M. Shulaker[1]*

*Nature 2019*



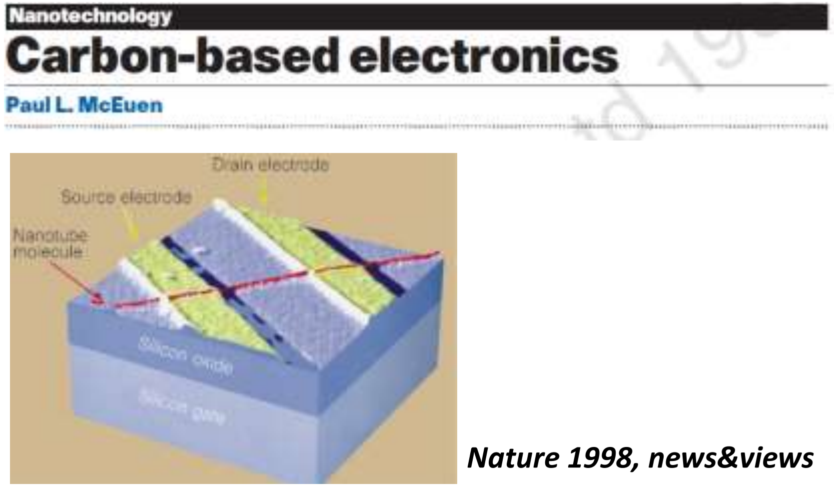
LETTER

doi:10.1038/nature12502

## Carbon nanotube computer

*Nature 2013*

# Carbon-based Electronics ?

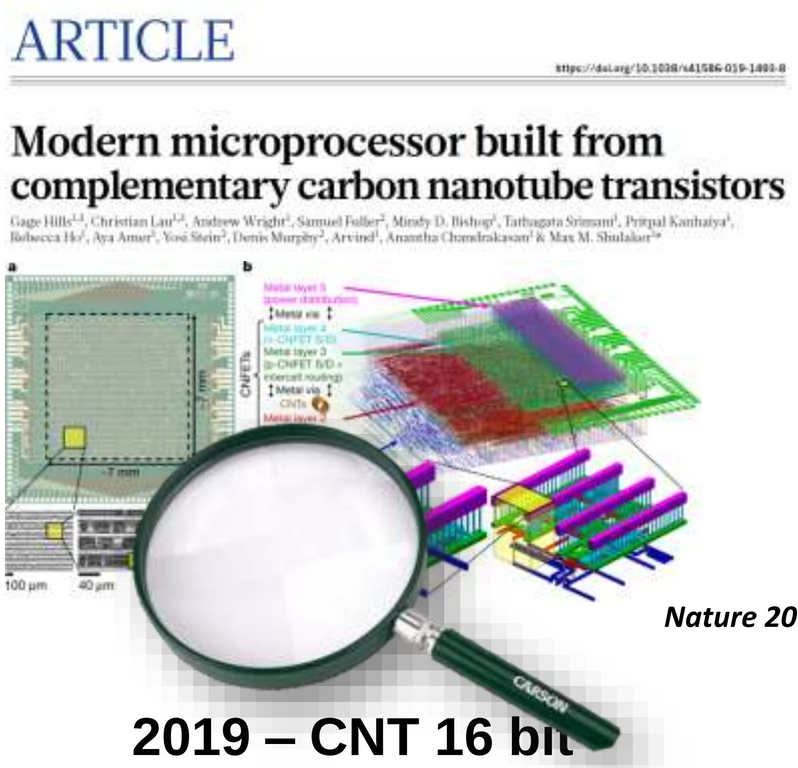


**Nanotechnology**

## Carbon-based electronics

**Paul L. McEuen**

*Nature 1998, news&views*



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*Nature 2019*

**1998 – Research Devices,**
**CNT Transistor**

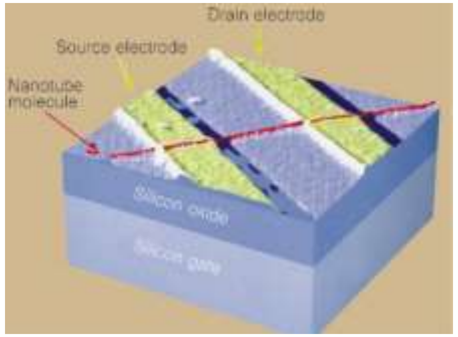
**2019 – CNT 16 bit**
**Processor**

# Carbon-based Electronics ?

Nanotechnology

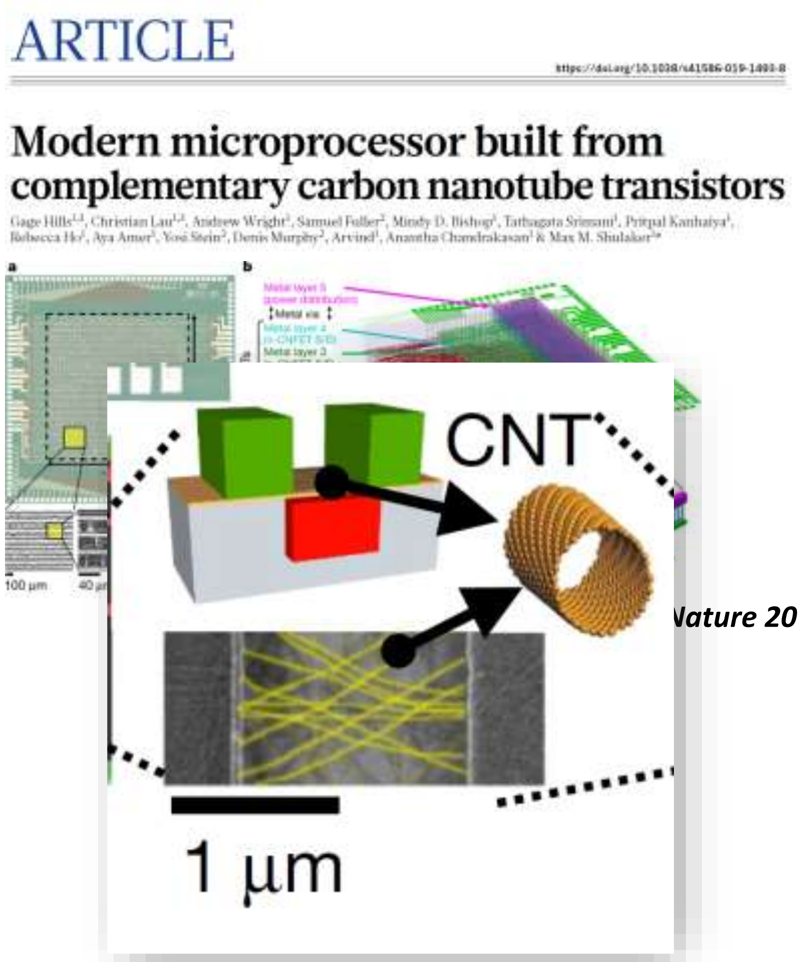
**Carbon-based electronics**

**Paul L. McEuen**



*Nature 1998, news&views*

**1998 – Research Devices, CNT Transistor**



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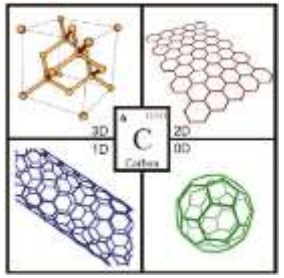
*Nature 2019*

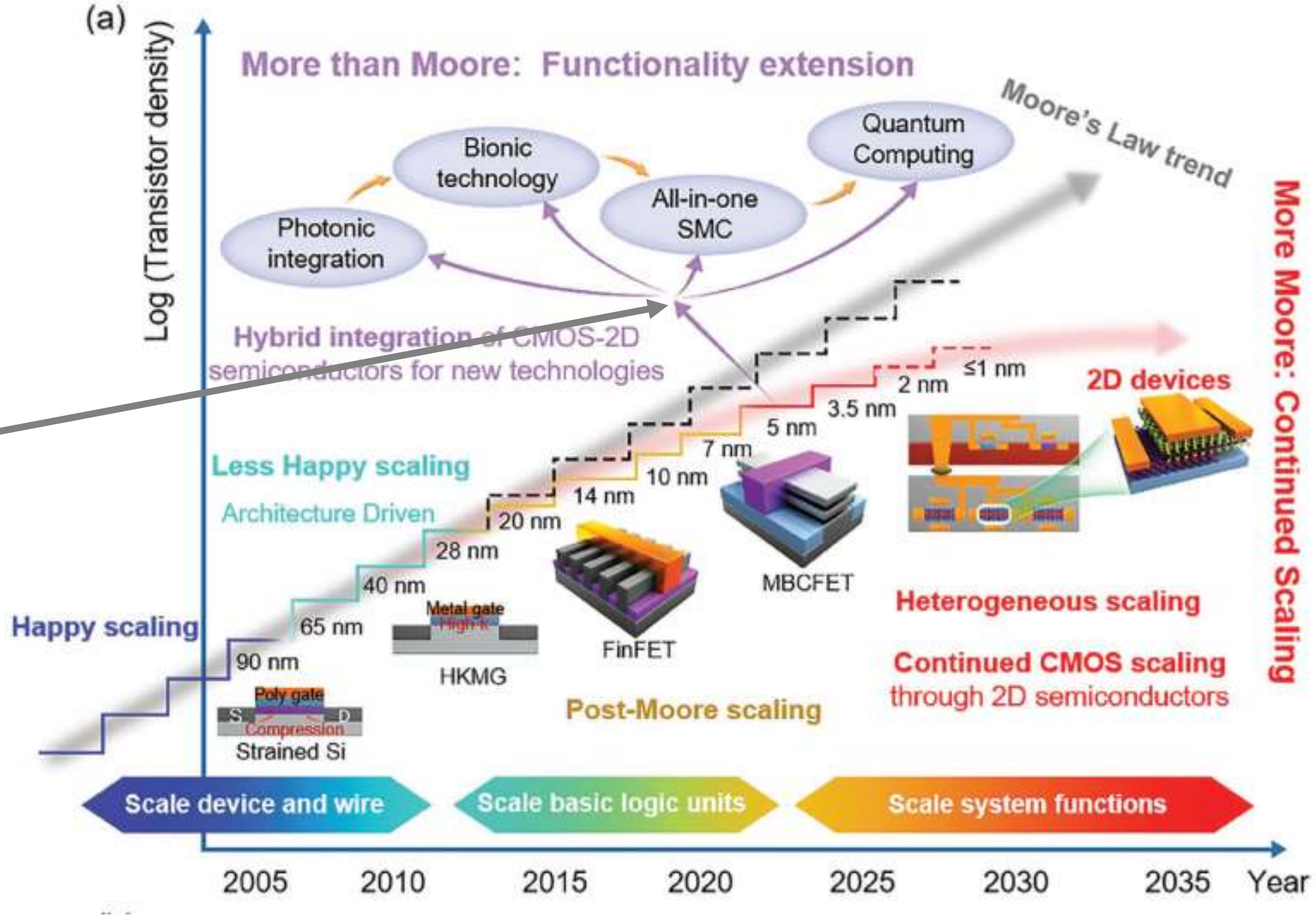
*Still, not individual Carbon Nanotubes …*

# carbon-based electronics



**materials**

**C-based materials**



*Wang et al., Adv. Mat. (2022)*

# *electronics with molecules ?*

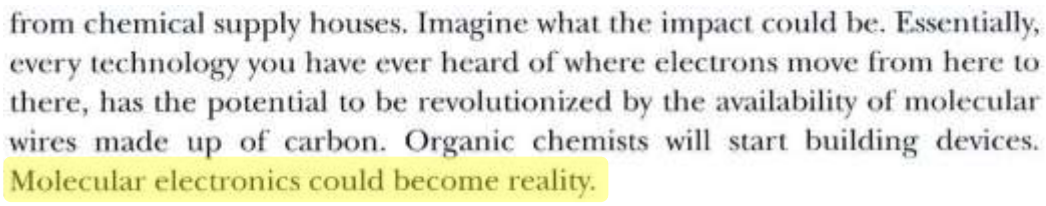
editorial

***Nature Nanotech. 2013***

## Does molecular electronics compute?

The field of molecular electronics originally set out to build computers, but silicon-based technology is unlikely to be replaced anytime soon. Nevertheless, the field has developed into a highly interdisciplinary endeavour, which could have a variety of ramifications that extend beyond computing.

*Remember that …?*



from chemical supply houses. Imagine what the impact could be. Essentially, every technology you have ever heard of where electrons move from here to there, has the potential to be revolutionized by the availability of molecular wires made up of carbon. Organic chemists will start building devices. Molecular electronics could become reality.

***R.S. Smalley, Nobel lecture, 1996***

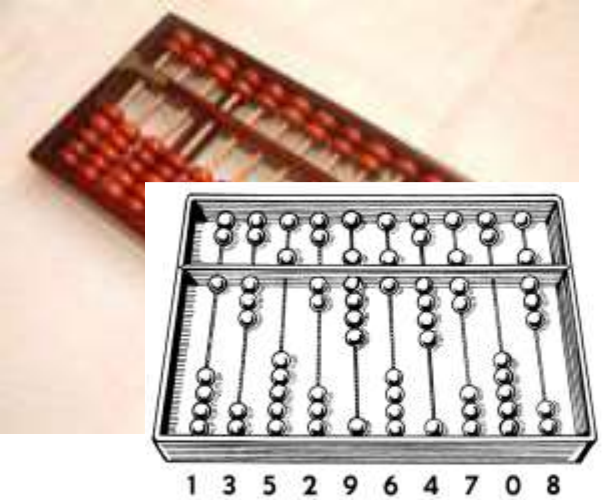
# Wait…. what is computing actually ?

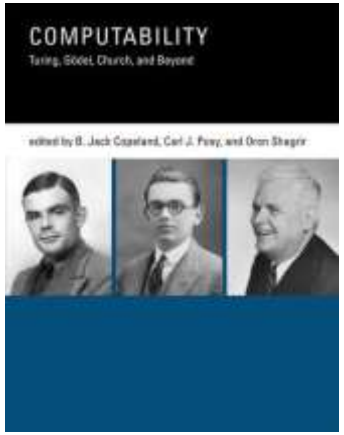
**Computing**

Denning, 2010; Horswill, 2008; wikipedia

# Wait…. what is computing actually ?

**Computing**





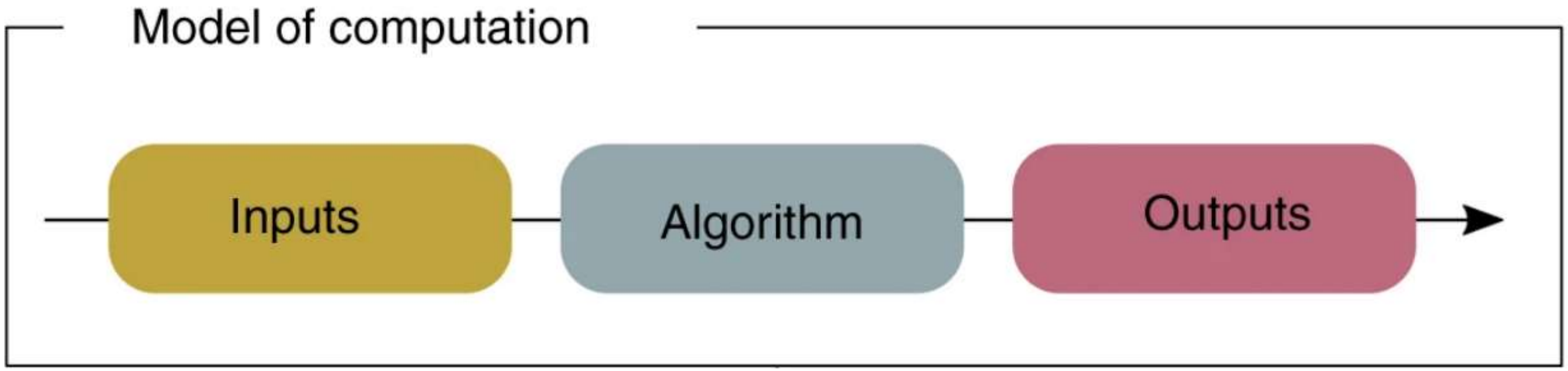
Computability:
**Turing, Gödel, Churc**h, and Beyond
Edited by B.J. Copeland, C.J. Posy,
O. Shagrir, MIT Press,

The first IBM system to
include Intel´s 80386 chip
Computerhistory.org

Mary Jackson,
Credit: NASA

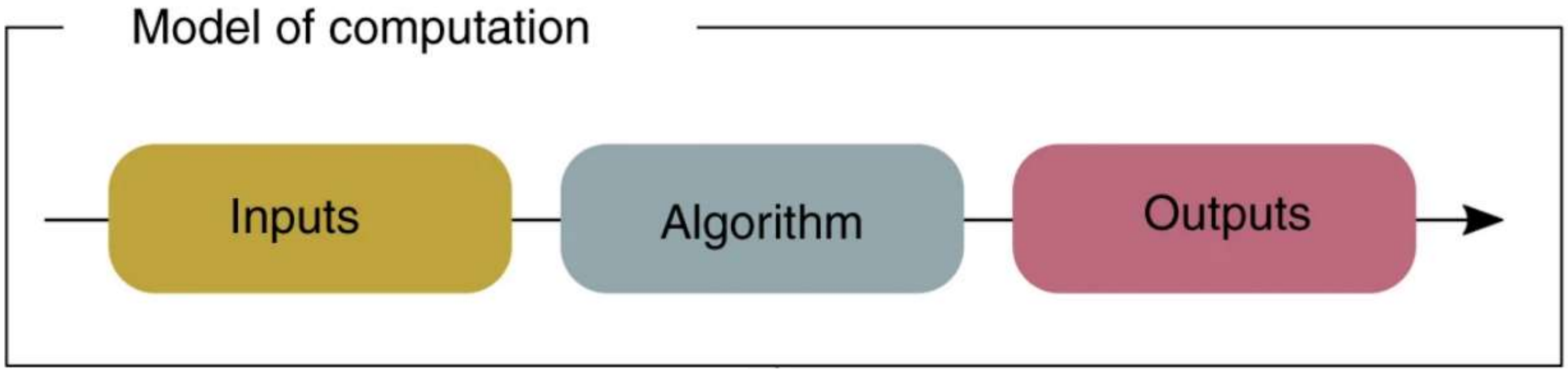
Denning, 2010; Horswill, 2008; wikipedia

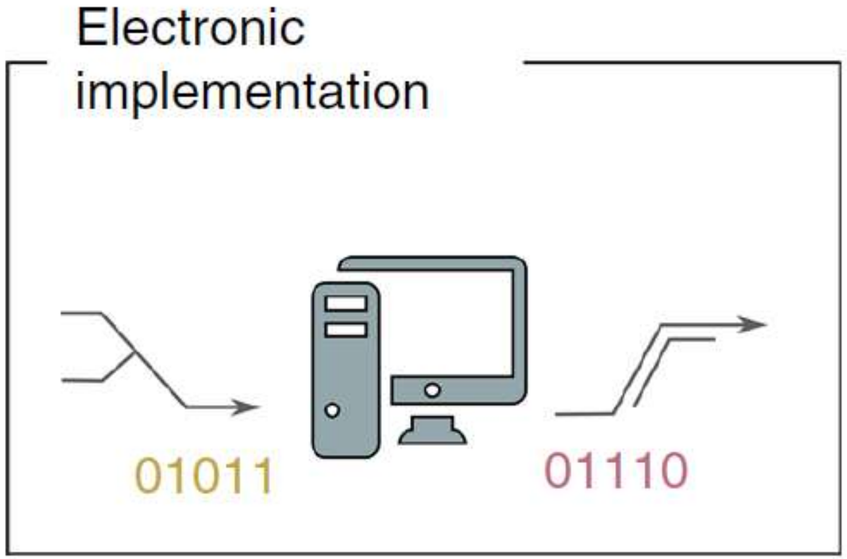
# Computation: Model and Implementation



Grozinger et al., Nat. Comm. (2019)

# Computation: Model and Implementation



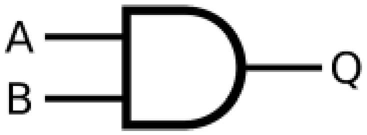


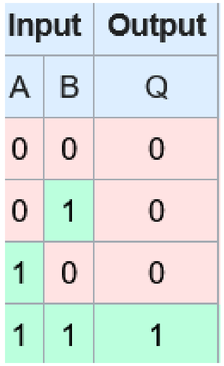
**Binary nb** **0 1 0 1 1** = 0 + 8 + 0 + 2 + 1 = 11

**Weight** $2^4$ $2^3$ $2^2$ $2^1$ $2^0$

16 8 4 2 1

**Operations**
Logic gates
AND





| Input | | Output |
|---|---|---|
| A | B | Q |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

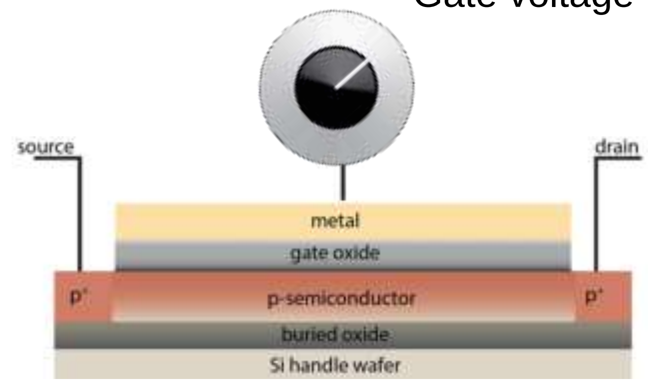
Grozinger et al., Nat. Comm. (2019)

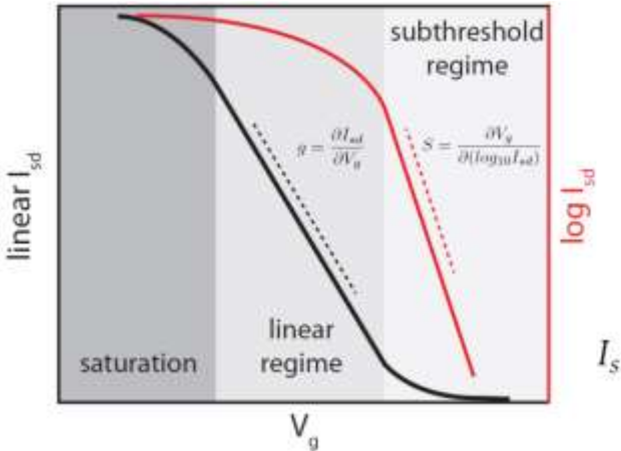
# Electronic Computation: Physical Implementation

## **Electronic Switch (0, 1)**

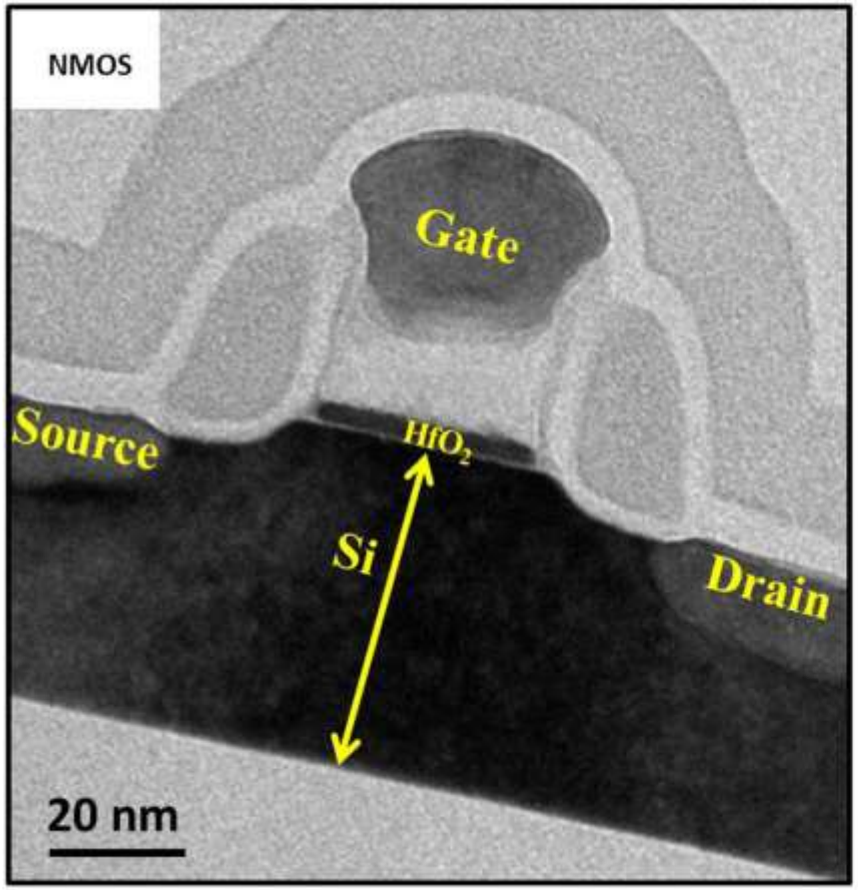
Field-Effect Transistor (MOSFET)

Gate voltage $\boldsymbol{V_g}$





$$I_{sd} = \mu C^{\square}_{ox} \frac{W}{L}(V_g - V_{fb})V_{sd}$$



https://www.nature.com/articles/s41598-017-07418-y