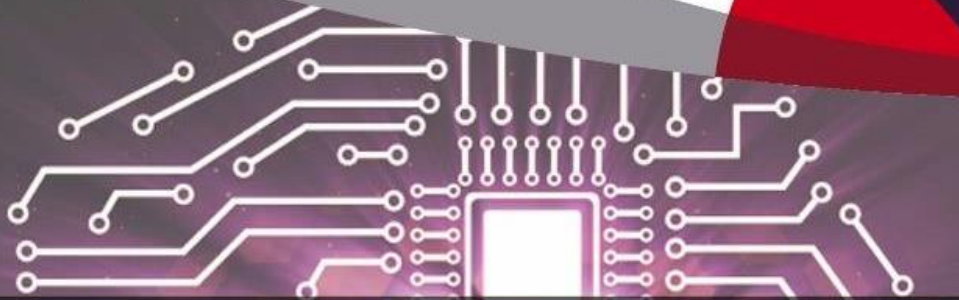


The Quest for Novel Materials for Light Energy and Quantum Computing applications.



يوم السبت الموافق ٢٠١٨/٧/٧
الساعة ٦ مساءً بتوقيت القاهرة
علي صفحة علماء مصر علي Facebook



Dr. Elham Fadaly

PhD Candidate

Eindhoven University of Technology

My Background

[Sep 2008 – Jun 2013]

[The American University in Cairo (AUC)]

[Cairo, Egypt]

- Bachelor of Science (BSc.) in Electronics Engineering

[Jan 2011 – Jun 2011]

[Drexel University]

[Pennsylvania, The United States]

- Exchange Program for studying a semester abroad in the Electrical Engineering Department.

[Sep 2013 – Jun 2014]

[Katholieke Universiteit Leuven (KU LEUVEN)]

[Leuven, Belgium]

[Sep 2014 – Aug 2015]

[Chalmers University of Technology]

[Gothenburg, Sweden]

- Master of Science (MSc.)

Erasmus Mundus Masters of Nanoscience and Nanotechnology, Nanoelectronics track.

[Sep 2015 – Jan 2017]

[Delft University of Technology]

[Delft, Netherlands]

[Feb 2017 – Feb 2020]

[Eindhoven University of Technology]

[Eindhoven, Netherlands]

- Doctor of Philosophy (PhD) candidate in the Applied Physics Department, advanced Nanomaterials and Devices group

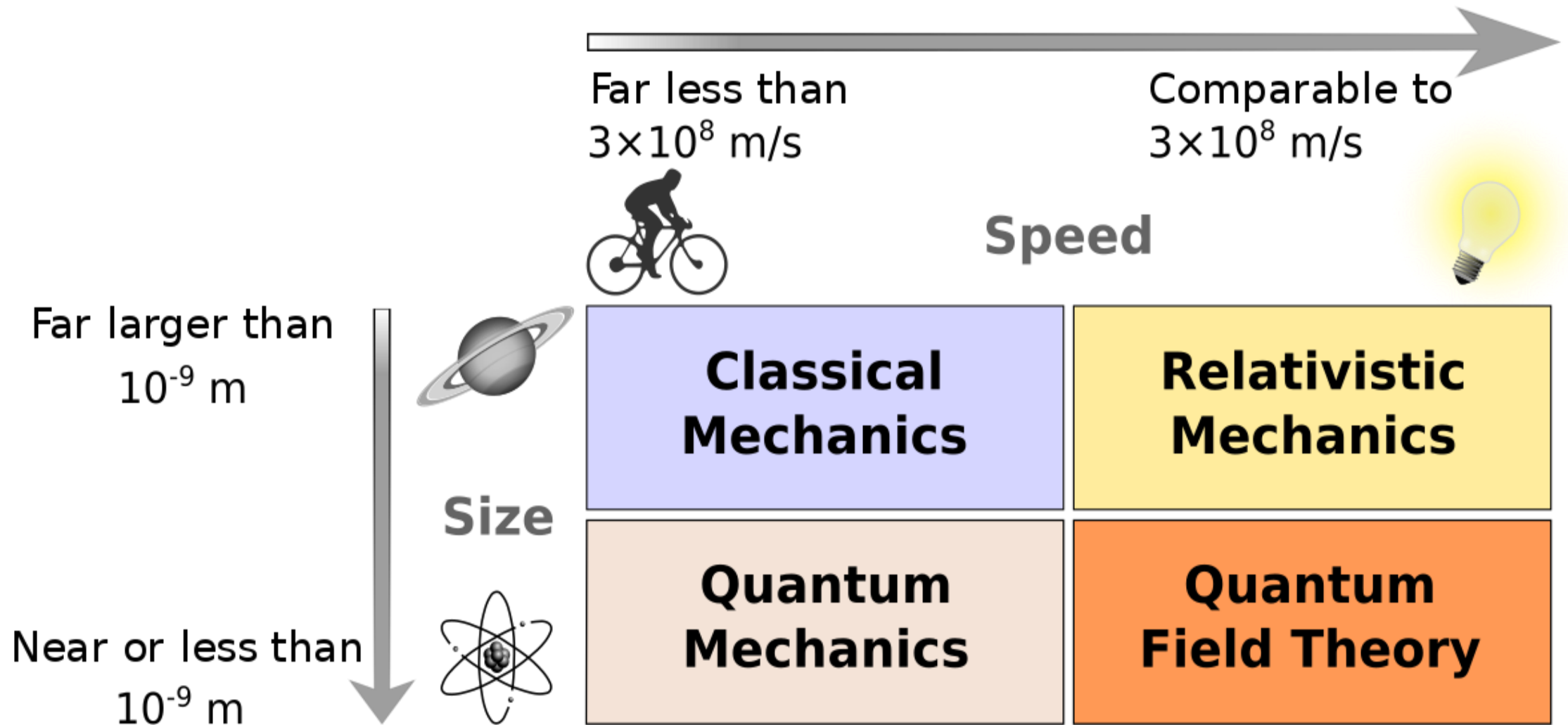
RELATIVITY

CLASSICAL
PHYSICS

PHYSICS

QUANTUM PHYSICS

Physics



CLASSICAL PHYSICS

ISAAC NEWTON

LAWS OF MOTION

CALCULUS

LAW OF UNIVERSAL GRAVITATION

GRAVITY

ORBITS

OPTICS

PRISM

MICROSCOPE

TELESCOPE

ELECTROMAGNETISM

ELECTRIC FIELDS

MAGNETIC FIELDS

ELECTRICITY

ELECTRICITY

LIGHT

THERMODYNAMICS

ENERGY

HEAT

TEMPERATURE

ENTROPY

CLASSICAL MECHANICS

FLUID MECHANICS

FLOW

LIFT

AERODYNAMICS

CHAOS THEORY

RELATIVITY

CONSTANT SPEED OF LIGHT

ALBERT EINSTEIN

SPECIAL THEORY OF RELATIVITY

$E=mc^2$

TIME

SPACE

WAVES

TRANSVERSE

LONGITUDINAL

JAMES CLERK MAXWELL

ATOMIC THEORY

CONDENSED MATTER PHYSICS

QUANTUM INFORMATION

COMPUTERS

LASERS

GENERAL THEORY OF RELATIVITY

SPACETIME

QUANTUM FIELD THEORY

QUANTUM ELECTRODYNAMICS

NUCLEAR PHYSICS

FISSION

FUSION

QUANTUM PHYSICS

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PHILOSOPHY

Physics Map

PHILOSOPHY OF SCIENCE

FREE WILL

HOW COME?

NATURE OF REALITY

JUST...WHY?

THE CHASM OF IGNORANCE

THE FUTURE

QUANTUM GRAVITY

STRING THEORY

LOOP QUANTUM GRAVITY

DARK ENERGY

DARK MATTER

AND MANY MORE

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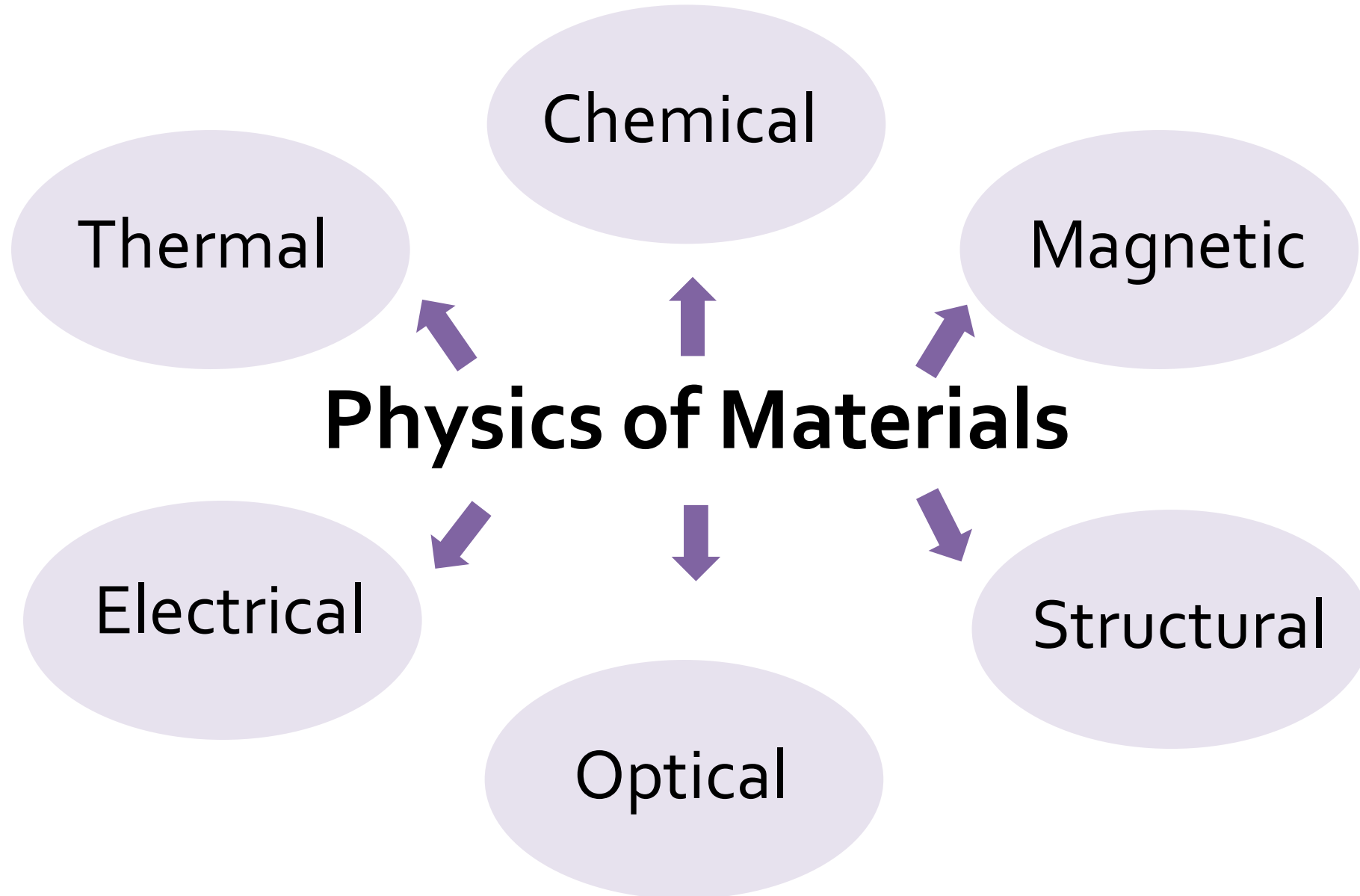
DARK ENERGY

DARK MATTER

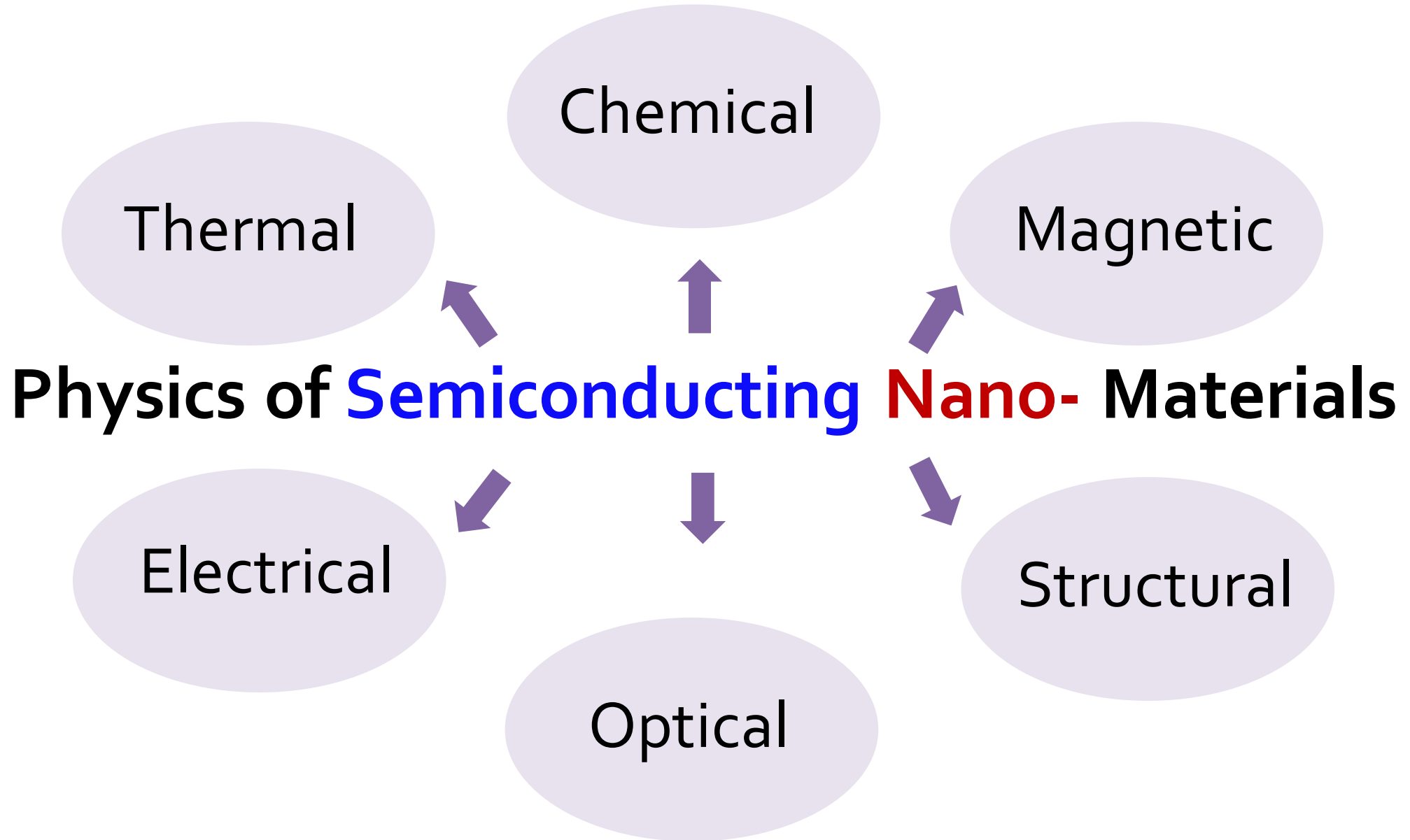
AND MANY MORE

PARTICLE PHYSICS

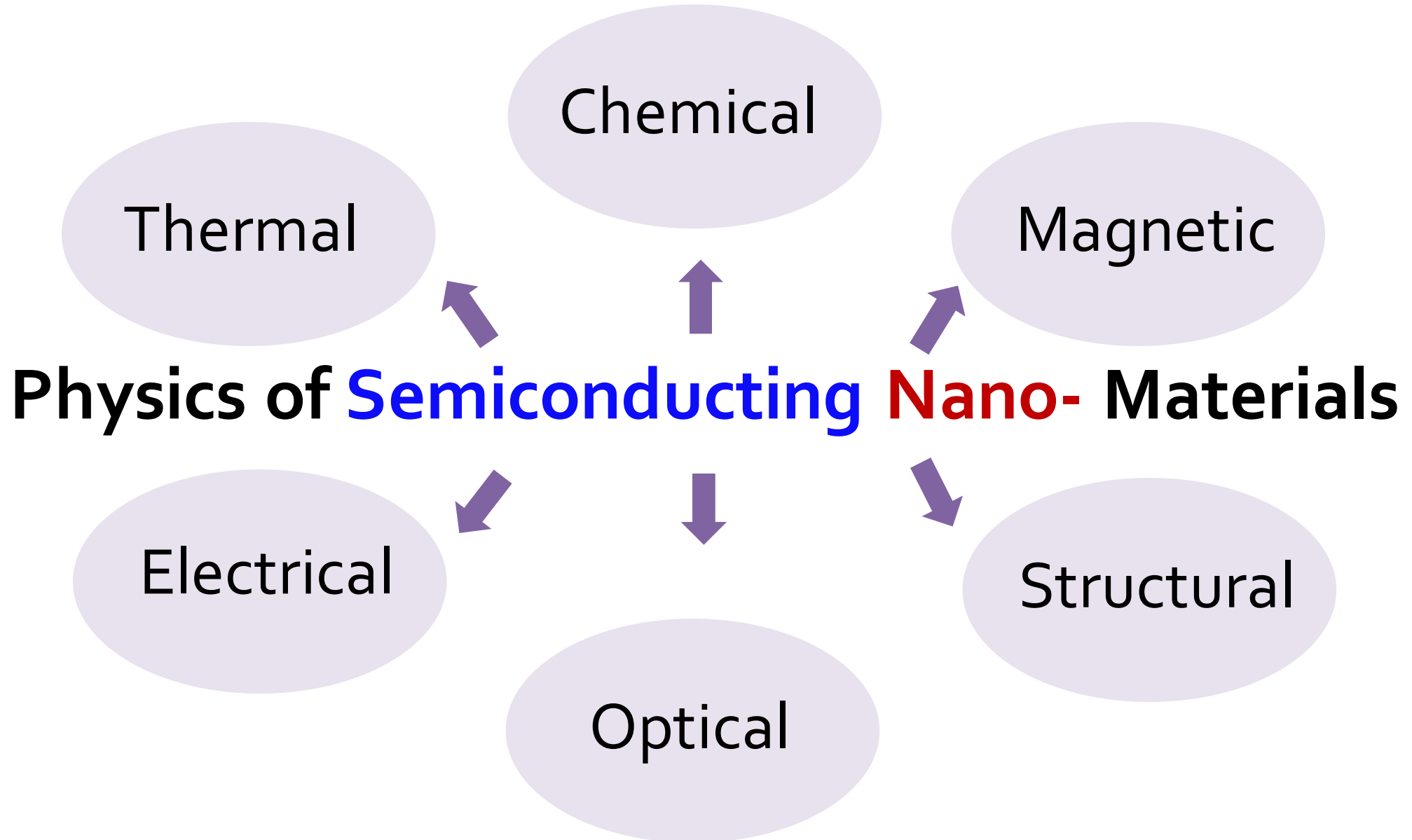
Condensed Matter Physics



Condensed Matter Physics



Condensed Matter Physics



Classification of Materials based on Bandgap

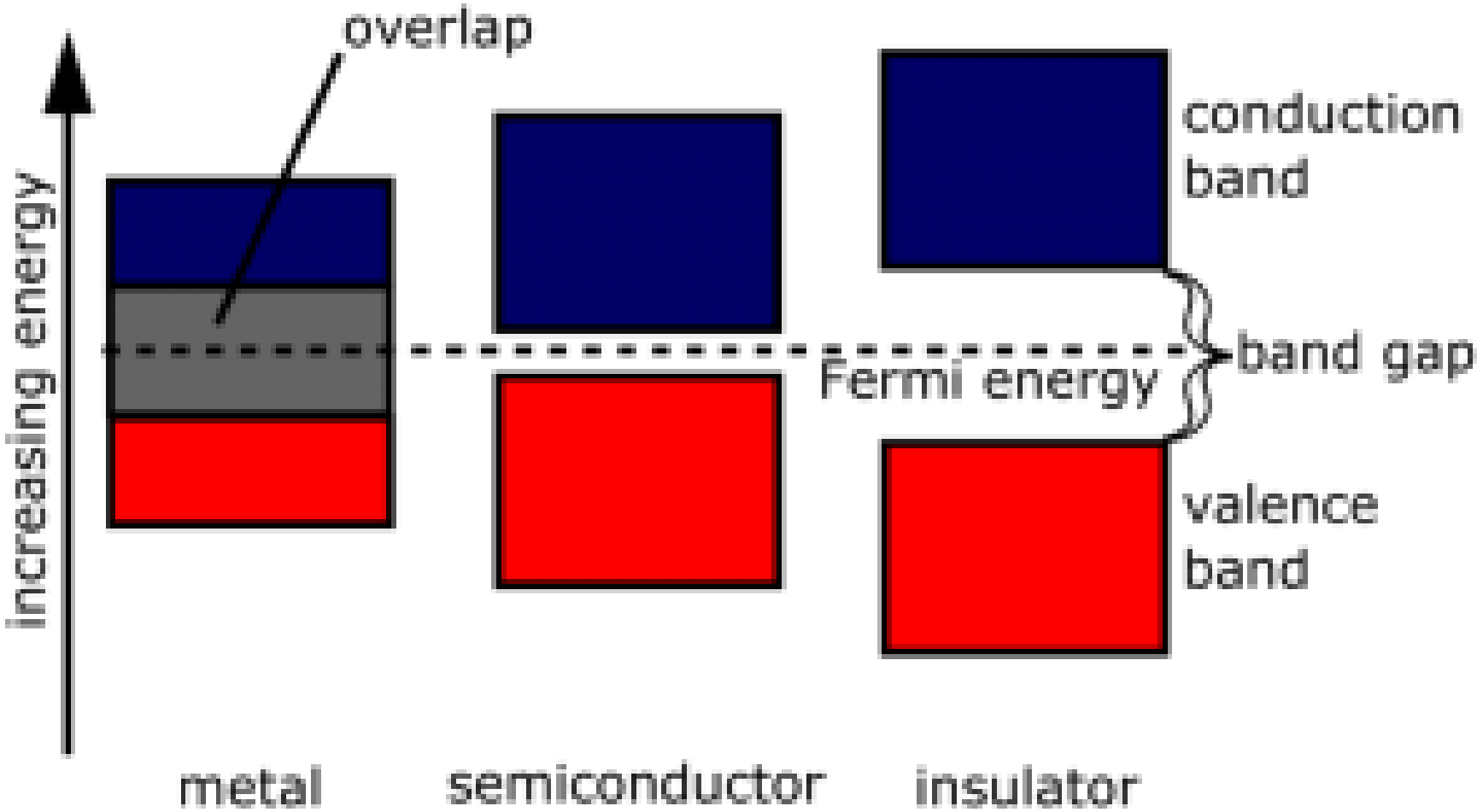


Image Courtesy: www.energyeducation.ca

Physics of **Semiconducting Nano-**Materials

- Simple/Elemental: Si, Ge

	IIIA	IVA	VA	VIA	
	5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.999 Oxygen	
	13 Al 26.9815385 Aluminium	14 Si 28.085 Silicon	15 P 30.973761998 Phosphorus	16 S 32.06 Sulfur	
IIB	30 Zn 65.38 Zinc	31 Ga 69.723 Gallium	32 Ge 72.630 Germanium	33 As 74.921595 Arsenic	34 Se 78.971 Selenium
	48 Cd 112.414 Cadmium	49 In 114.818 Indium	50 Sn 118.710 Tin	51 Sb 121.760 Antimony	52 Te 127.60 Tellurium
	80 Hg 200.592 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98040 Bismuth	84 Po 209 Polonium

Physics of **Semiconducting Nano-**Materials

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 - ✓ Binary : GaAs,

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 - ✓ **Ternary:** AlGaAs, HgCdTe
 - ✓ **Quaternary:** InGaAsP

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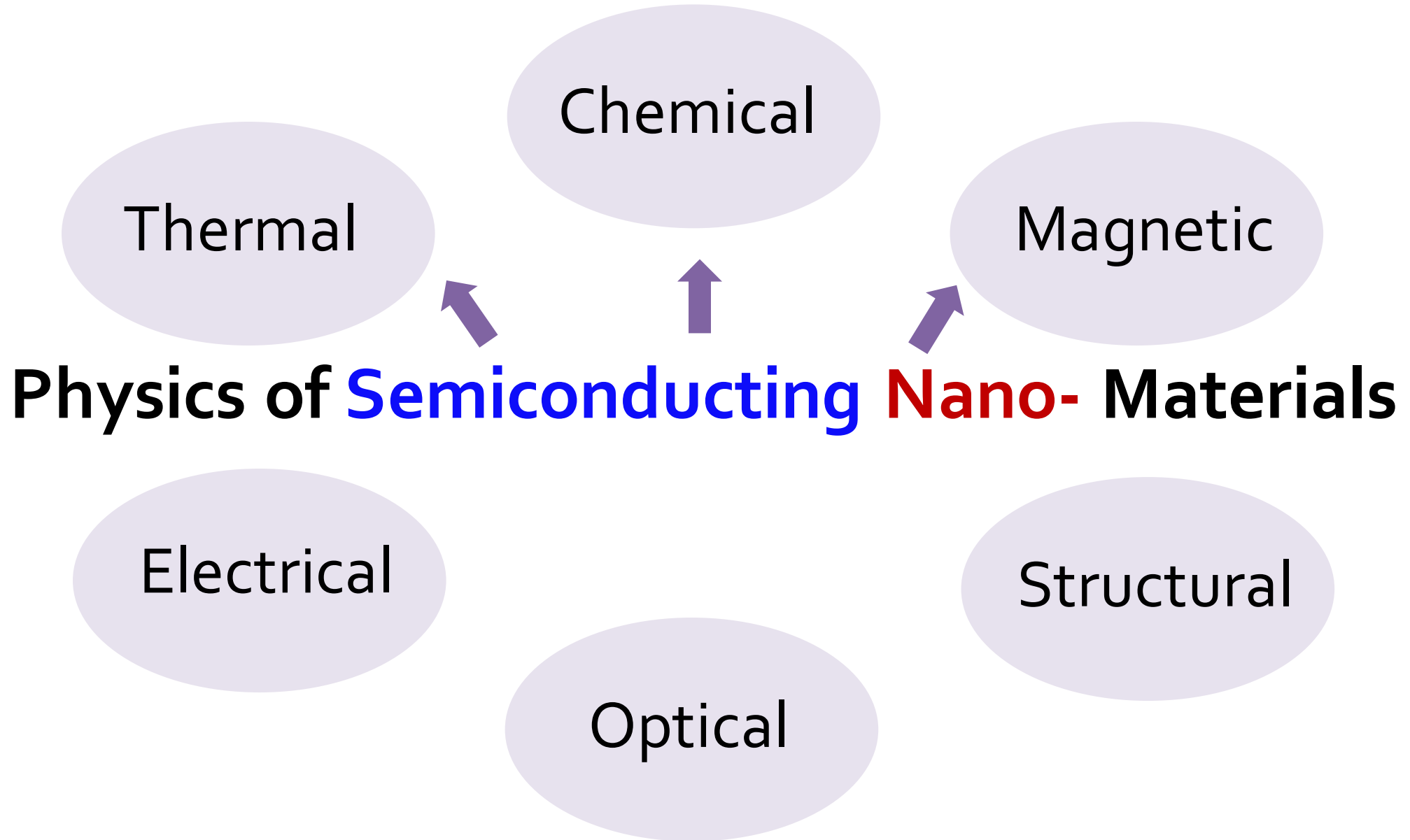
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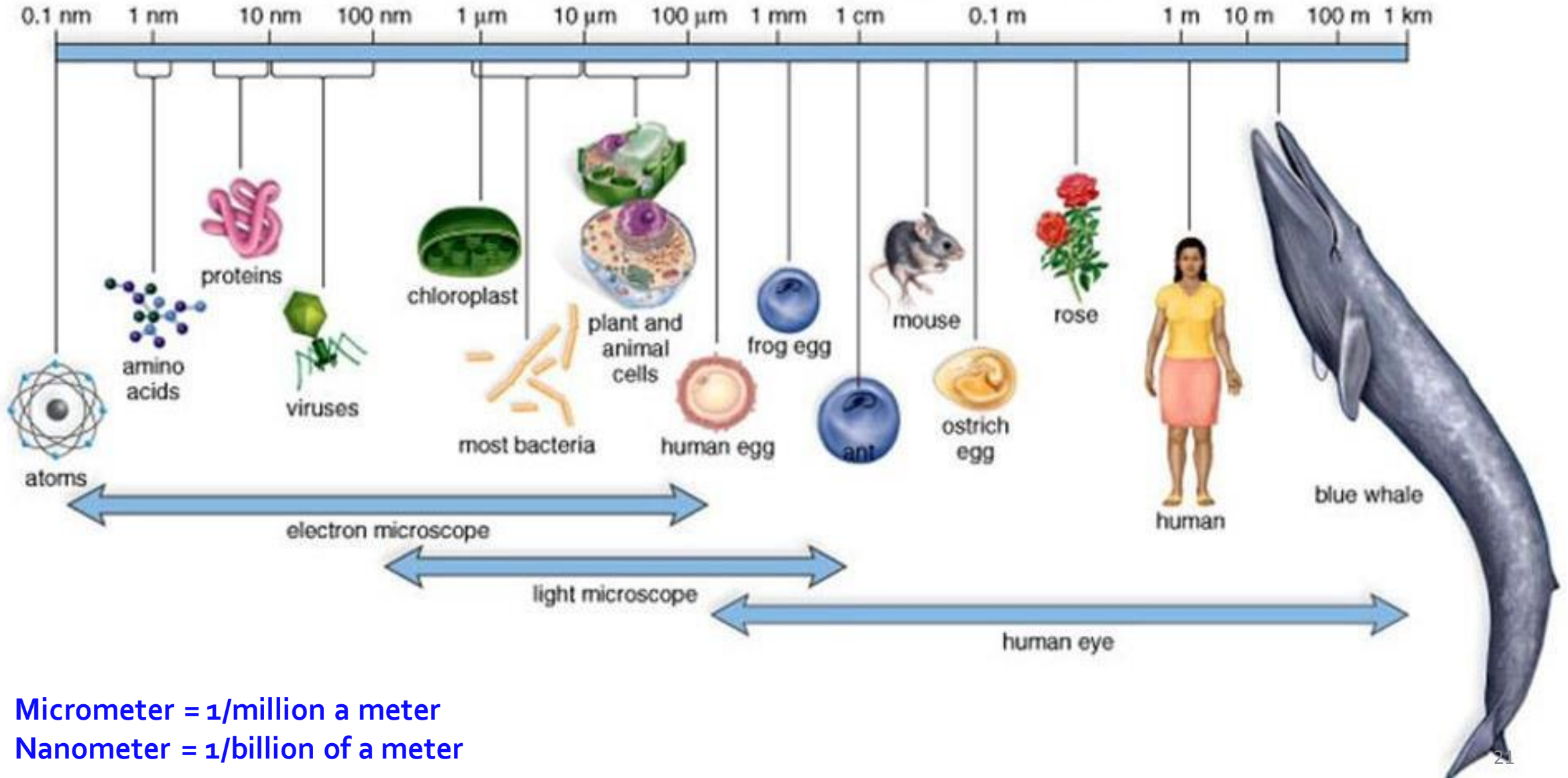
This is not an exhaustive list, it is just an example...

Condensed Matter Physics



Length Scale of Living Things

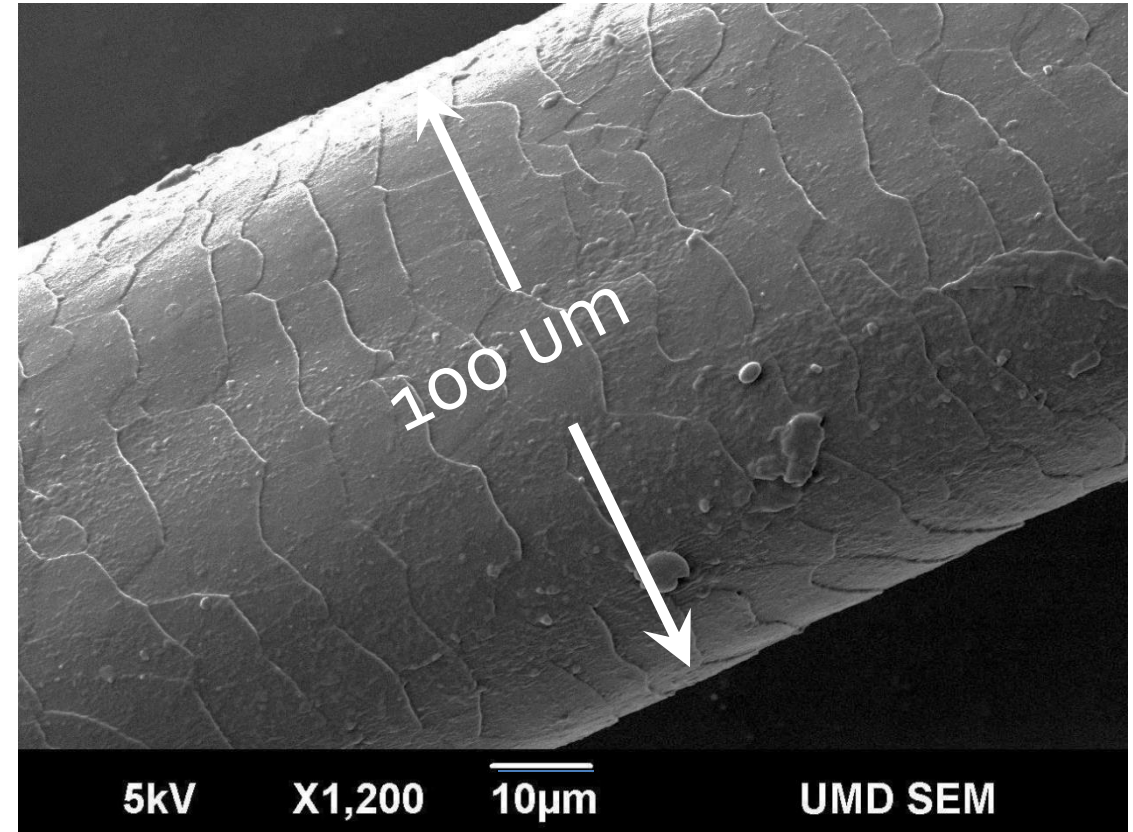
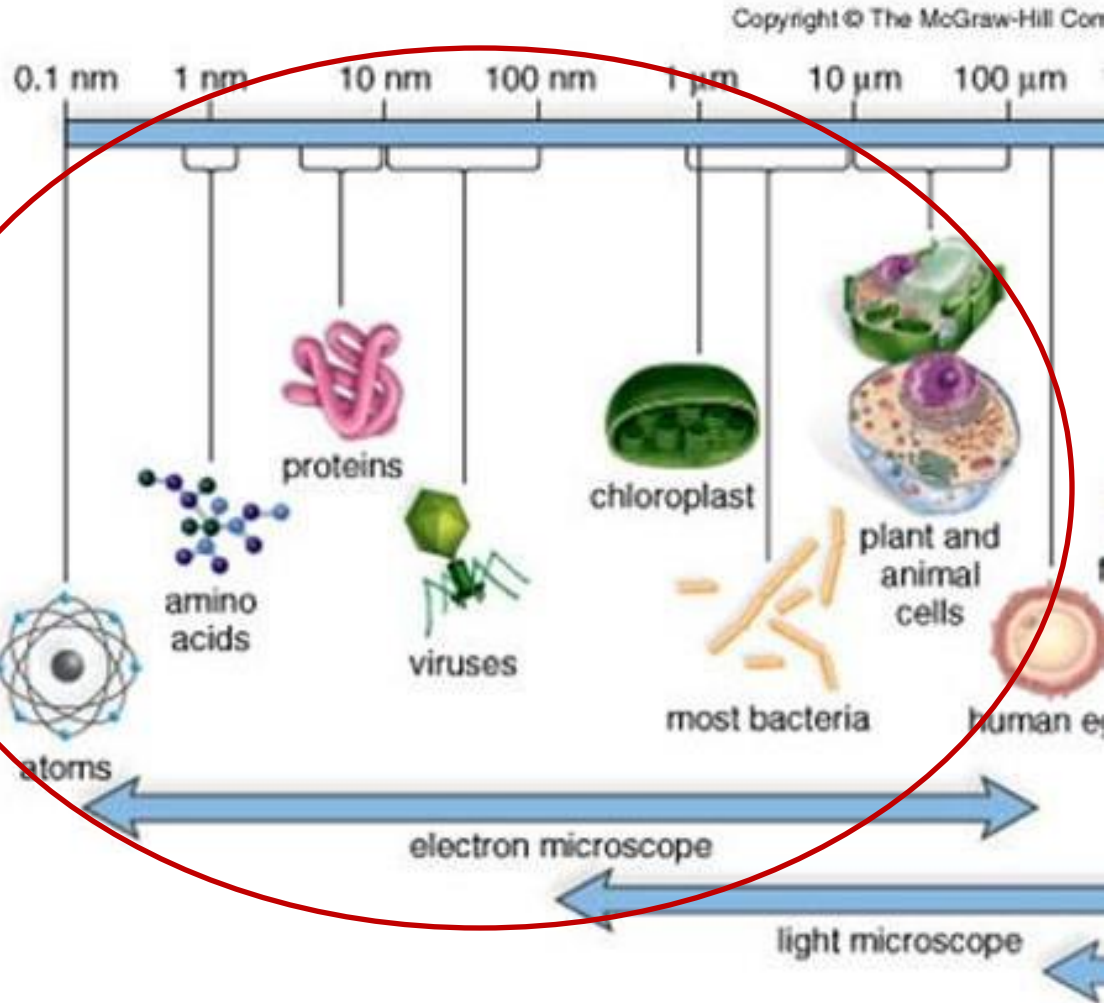
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Micrometer = 1/million a meter

Nanometer = 1/billion of a meter

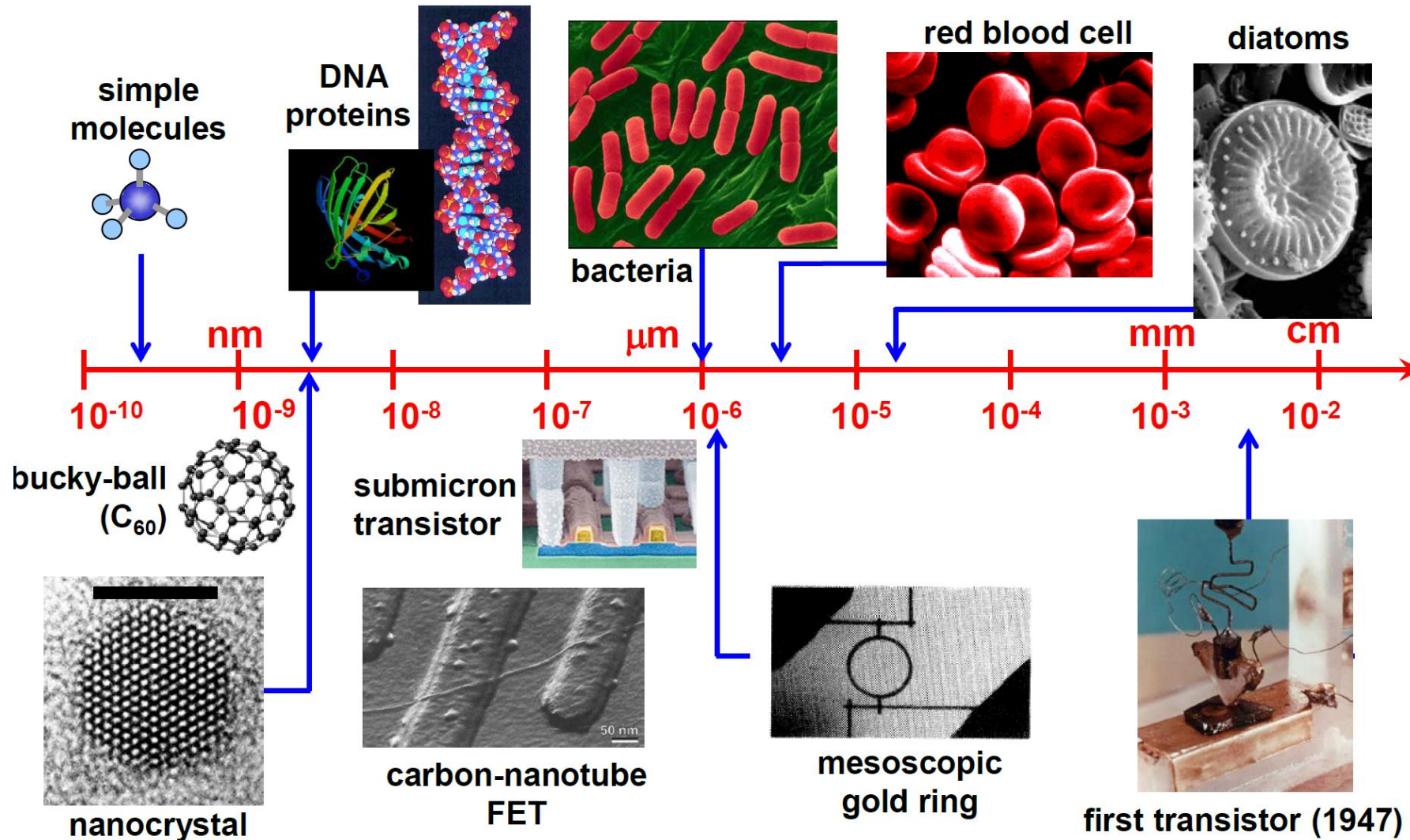
Length Scale of Nano-Materials



SEM Image of a Human Hair

Micrometer = 1/million a meter
Nanometer = 1/billion of a meter

Length Scale of Nano-Materials



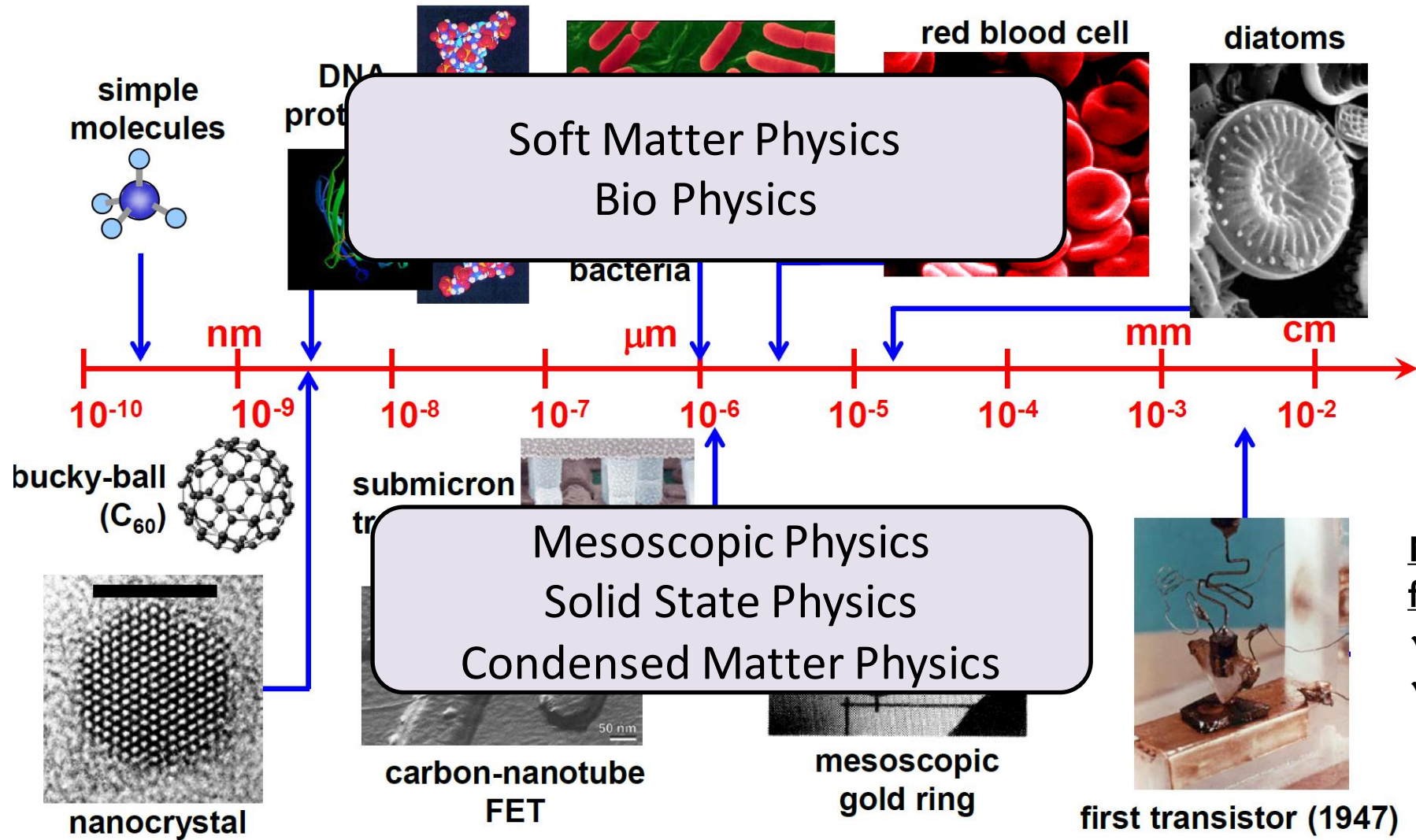
Bio- World:

- ✓ Aqueous Environments
- ✓ Room Temperature

Nano-Mesoscale nanomaterials for electronics:

- ✓ Mostly inorganic materials
- ✓ Mostly low Temperature

Length Scale of Nano-Materials



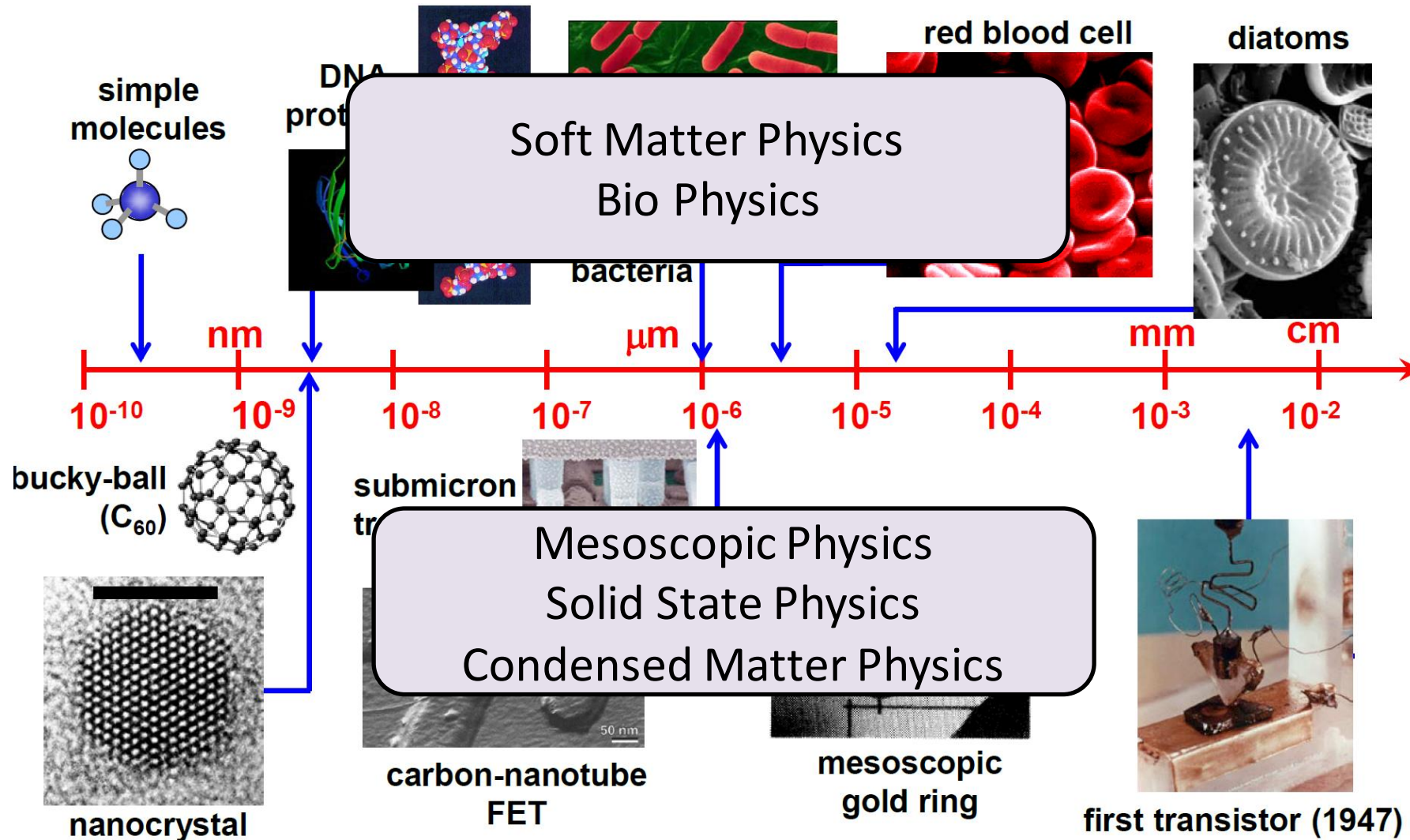
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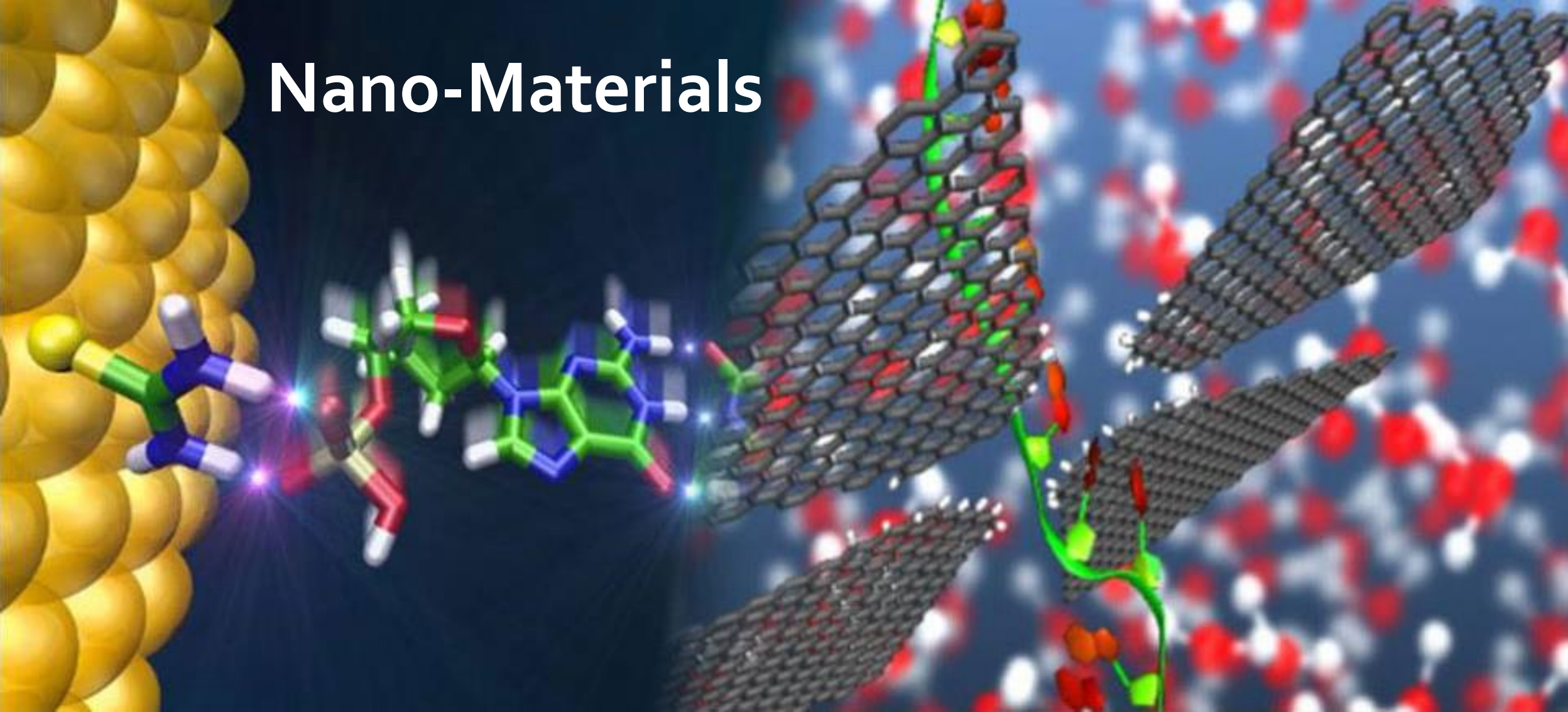
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Nano-Materials



Engineering/Manipulation/Control of materials on the atomic/molecular level

Nano-Materials



Unique Properties of Nanoscale Materials

Electrical
Optical
Thermal
Chemical
Mechanical
.... etc

Engineering/Manipulation/Control of materials on the atomic/molecular level

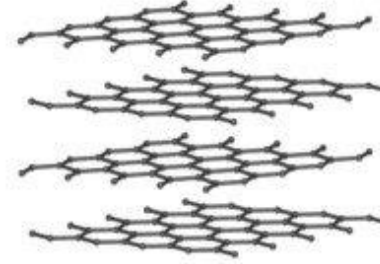
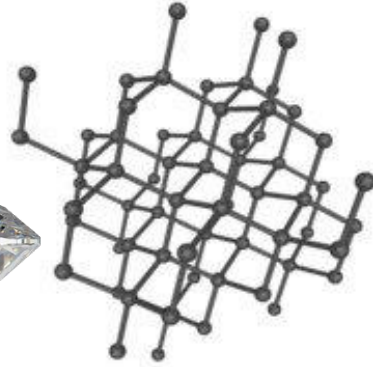
Example: Carbon Allotropes



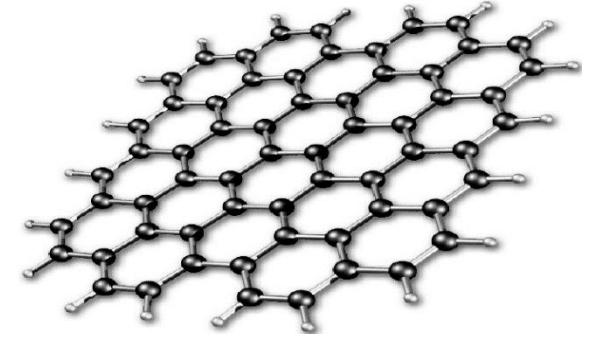
Charcoal
'Amorphous'



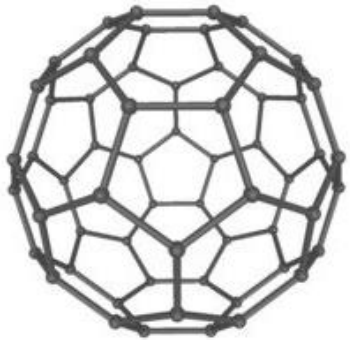
Diamond



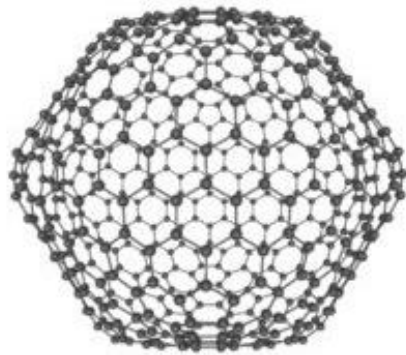
Graphite



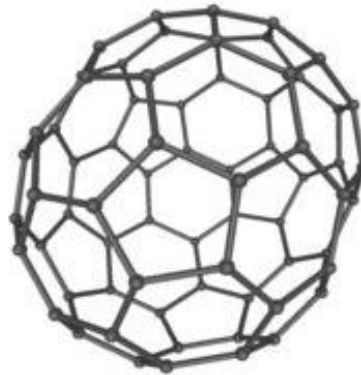
Graphene



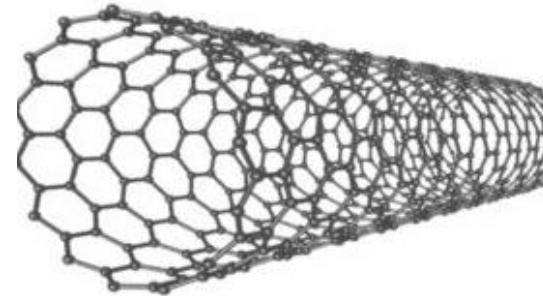
C60
buckminsterfullerene



C540, Fullerite



C70



single-walled
carbon nanotube



Multiwalled-
Carbon
nanotube

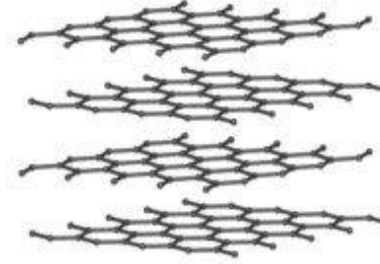
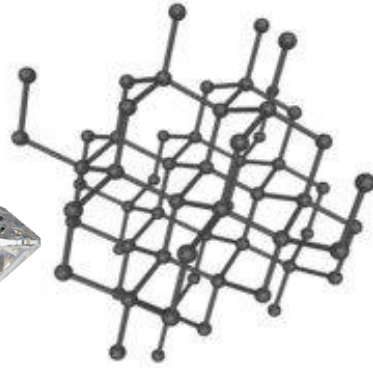
Example: Carbon Allotropes



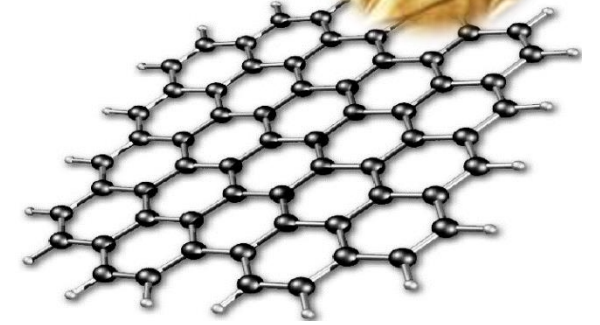
Charcoal
'Amorphous'



Diamond



Graphite

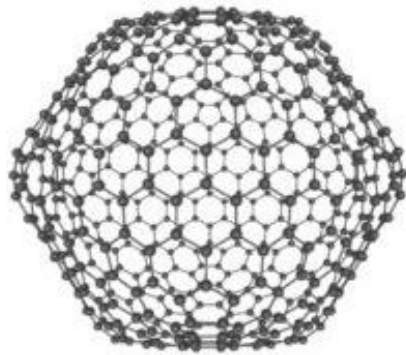


Physics Noble Prize 2010

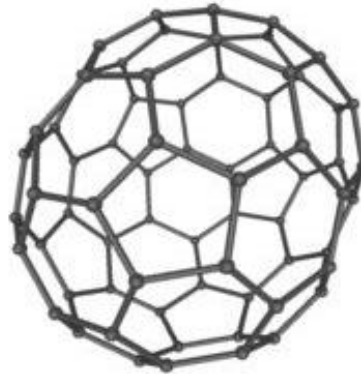
Graphene



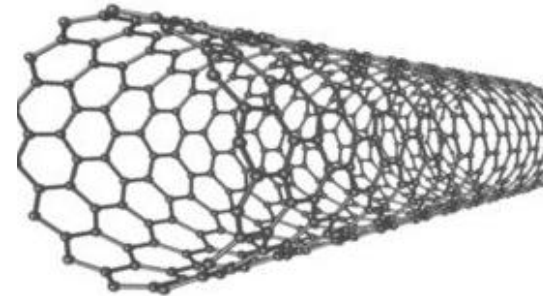
C60
buckminsterfullerene



C540, Fullerite



C70



single-walled
carbon nanotube



Multiwalled-
Carbon
nanotube

Chemistry Noble Prize 1996

Example: Carbon Allotropes

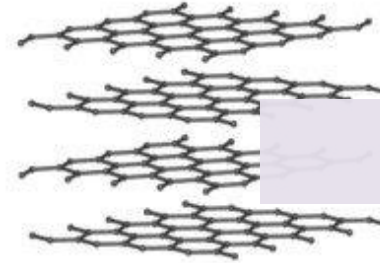
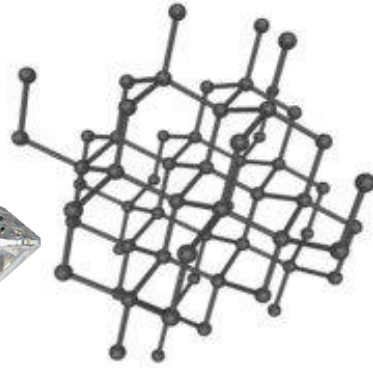


Charcoal
'Amorphous'

3D

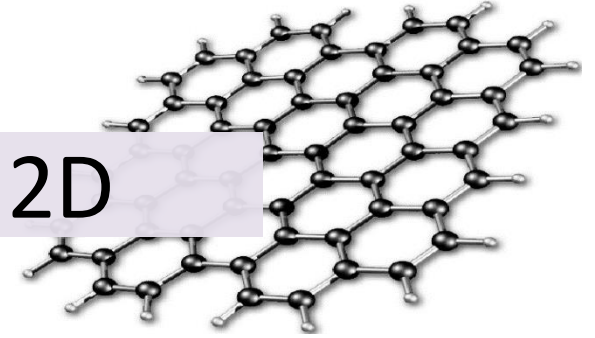


Diamond

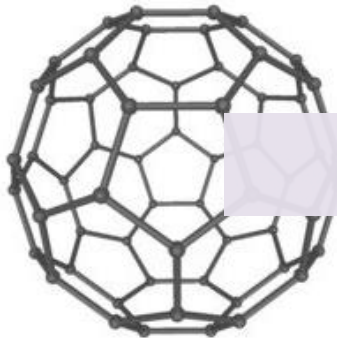


Graphite

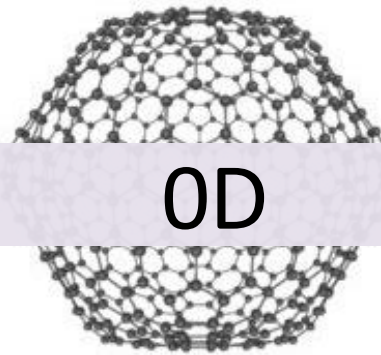
2D



Graphene



C60
buckminsterfullerene

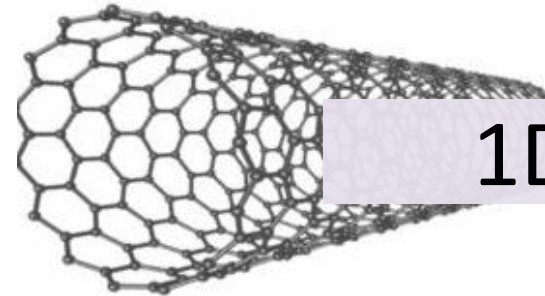


C540, Fullerite

0D

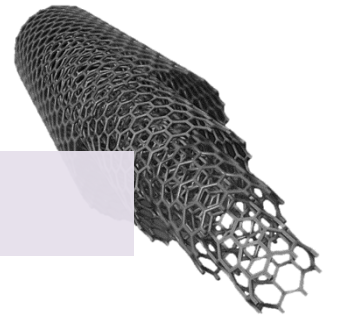


C70



single-walled
carbon nanotube

1D

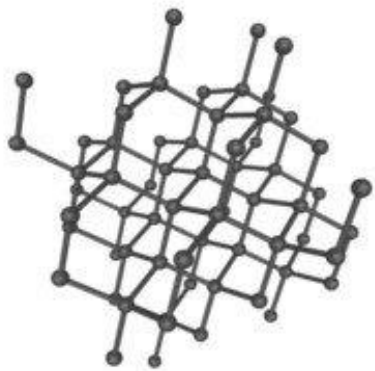


Multiwalled-
Carbon
nanotube

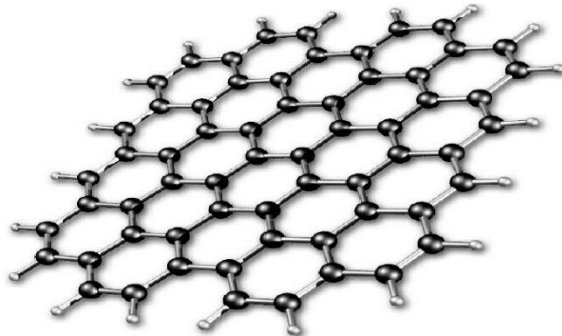
Classification of Nanomaterials based on Dimensionality

Classification is based on number of dimensions (x,y,z) confined to the nanoscale range:

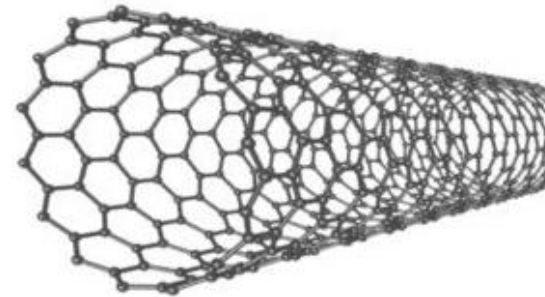
- **3D:** Bulk – No confinement, none of the dimensions is at nanoscale.
- **2D:** Quantum Wells–1 dimension (z) is at nanoscale, (x,y) are not.
- **1D:** Nanowires, Nanorods, Nanotubes – 2 dimensions (x,y) at nanoscale, (z) is not.
- **0D:** Quantum Dots, Nanoparticles- 3 dimensions (x,y,z) at nanoscale



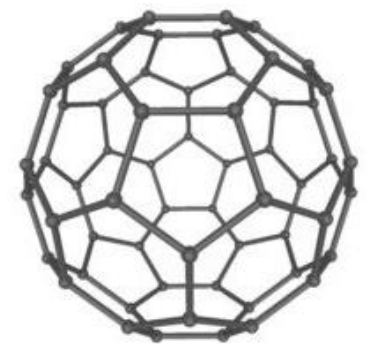
Diamond



Graphene



**single-walled
carbon nanotube**

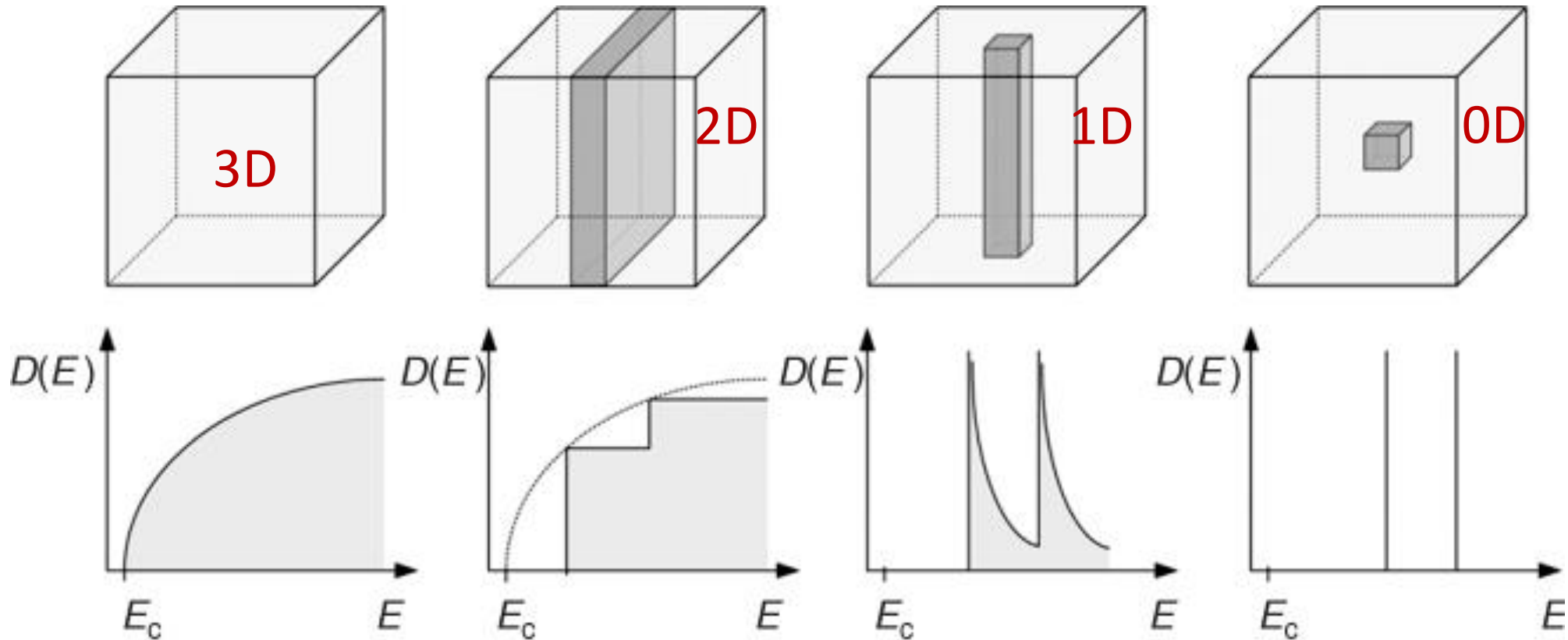


**C60
buckminsterfullerene**

Electronic Properties as a function of Dimensionality

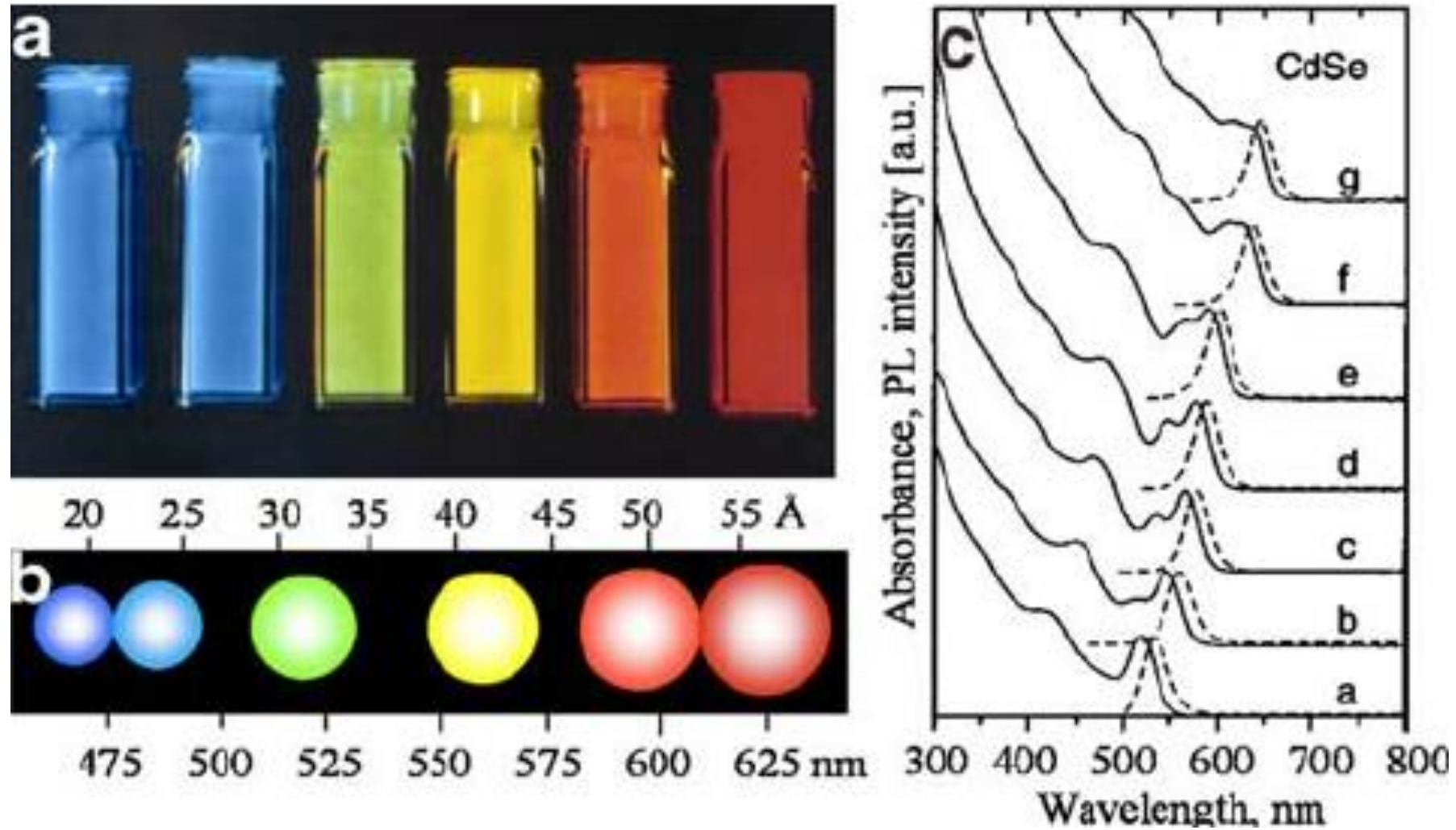
Quantum Confinement Concept
'Quantum Physics'

Different
Energy scales



How closely packed energy levels

Optical Properties as a function of Dimensionality

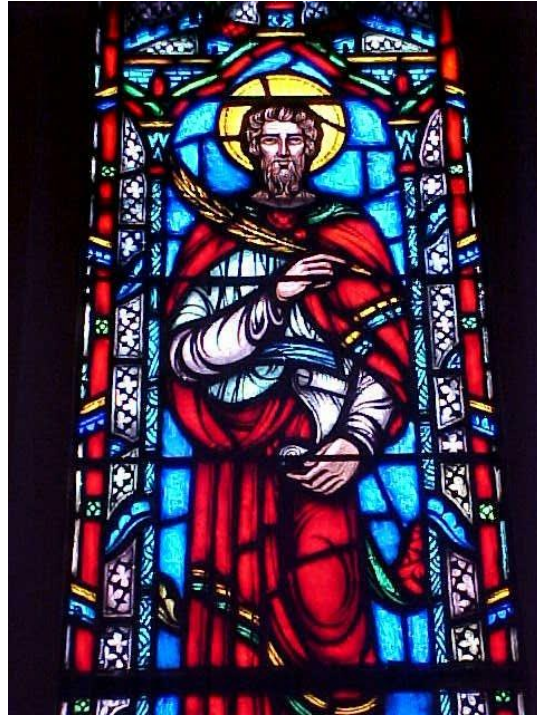


Optical Properties as a function of Dimensionality



<http://nano--tech.blogspot.com>

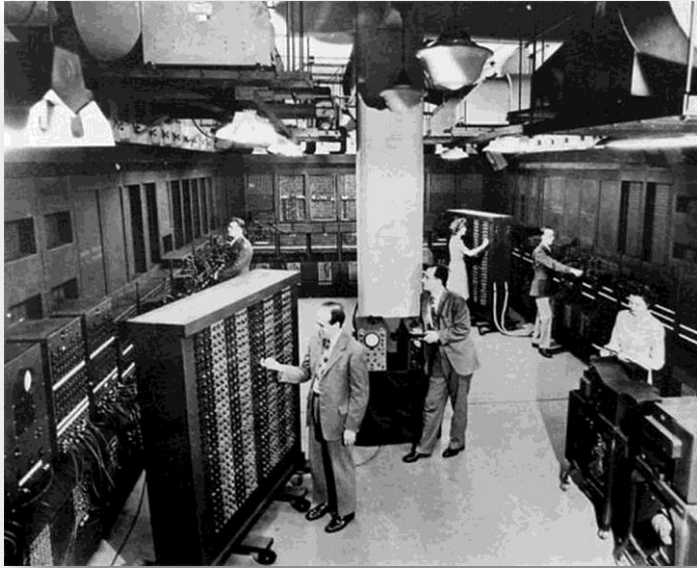
Stained Glass Art in the Medieval Era



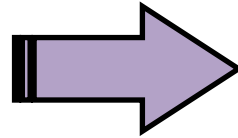
Samsung

Why new materials ... ?

New Functionalities, New Applications, Portable devices, affordable prices ,...etc



1945 - ENIAC



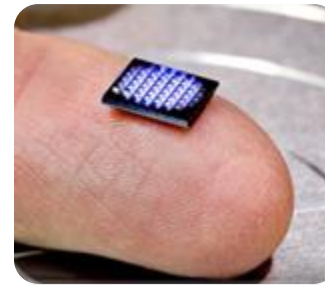
Portable PCs



Pocket Size Mobile Phones



1973- Motorola



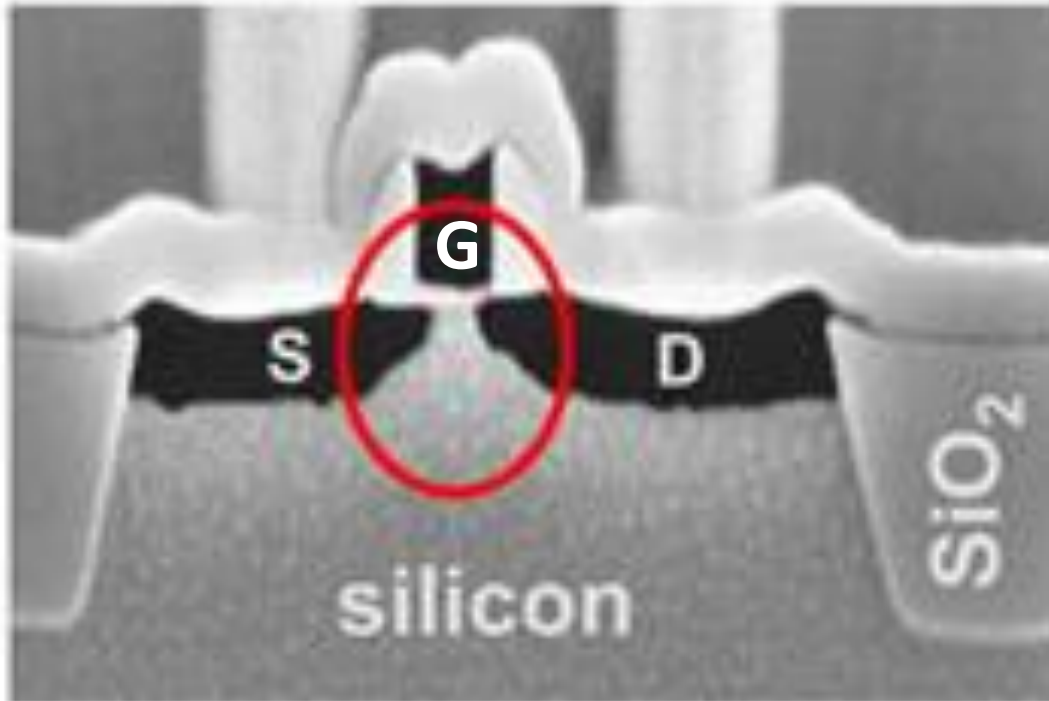
Cryptographic anchors-IBM



2018

Transistor- Building Block for computer Chips

Transistor



Texas Instruments, 1997

Closed Valve



Source

Drain

Open Valve



Source

Flow

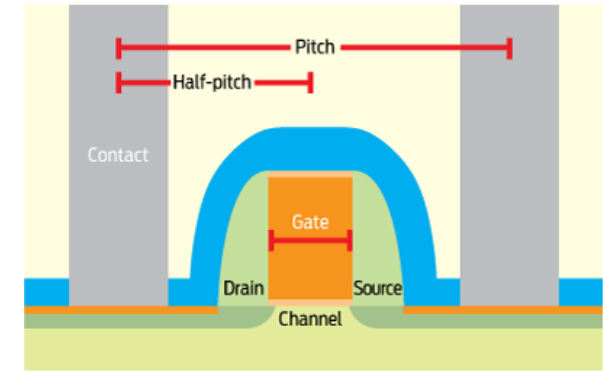
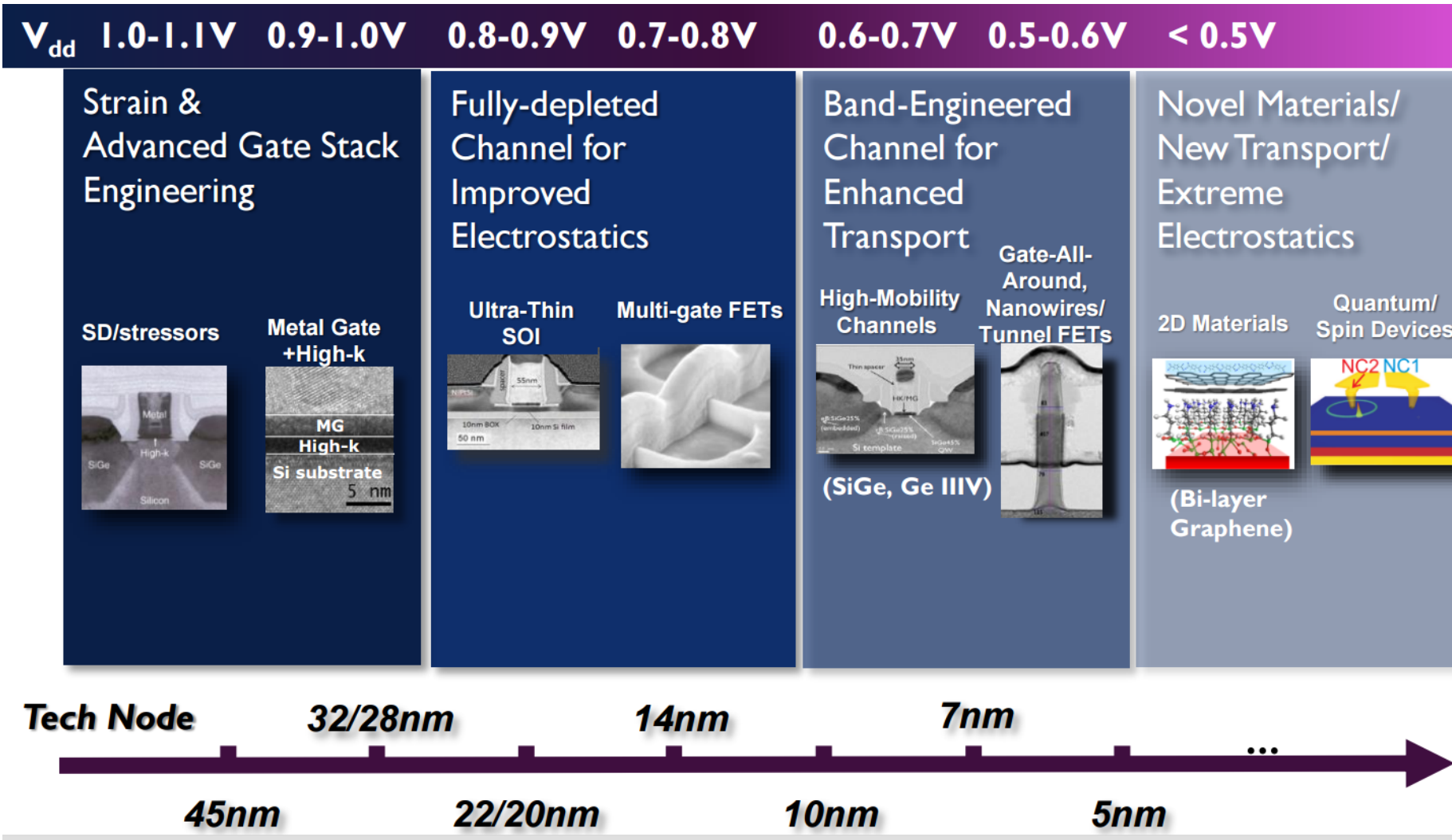
Drain

Moore's law as a driver for miniaturization

MOORE'S LAW ... NUMBER OF TRANSISTORS ON A CHIP DOUBLES EVERY TWO YEARS

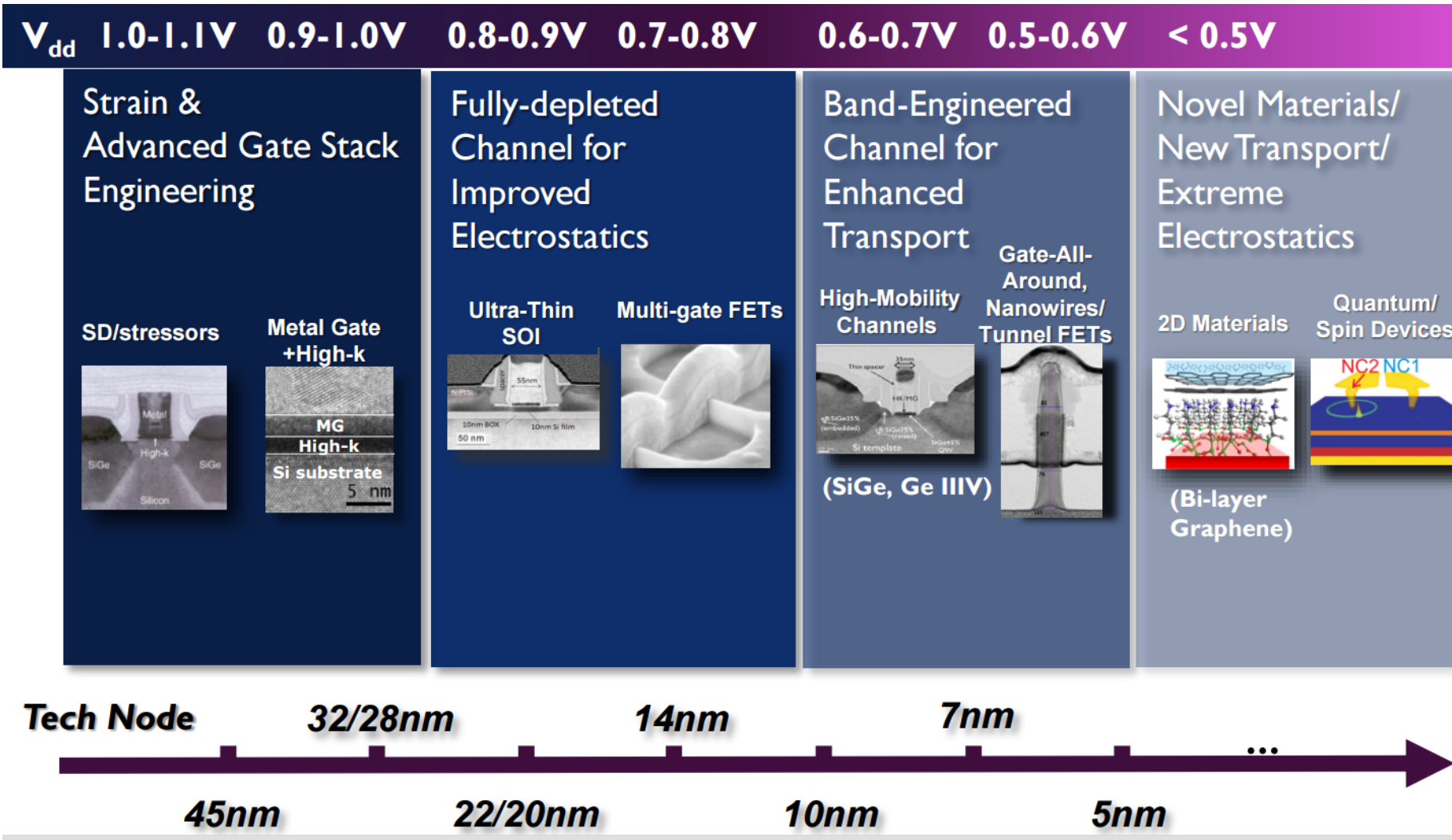


Transistors Technology Nodes- Miniaturization Trend



Technology Node Definition
= 1/2 Pitch b/w 2 Metal lines

Transistors Technology Nodes- Miniaturization Trend

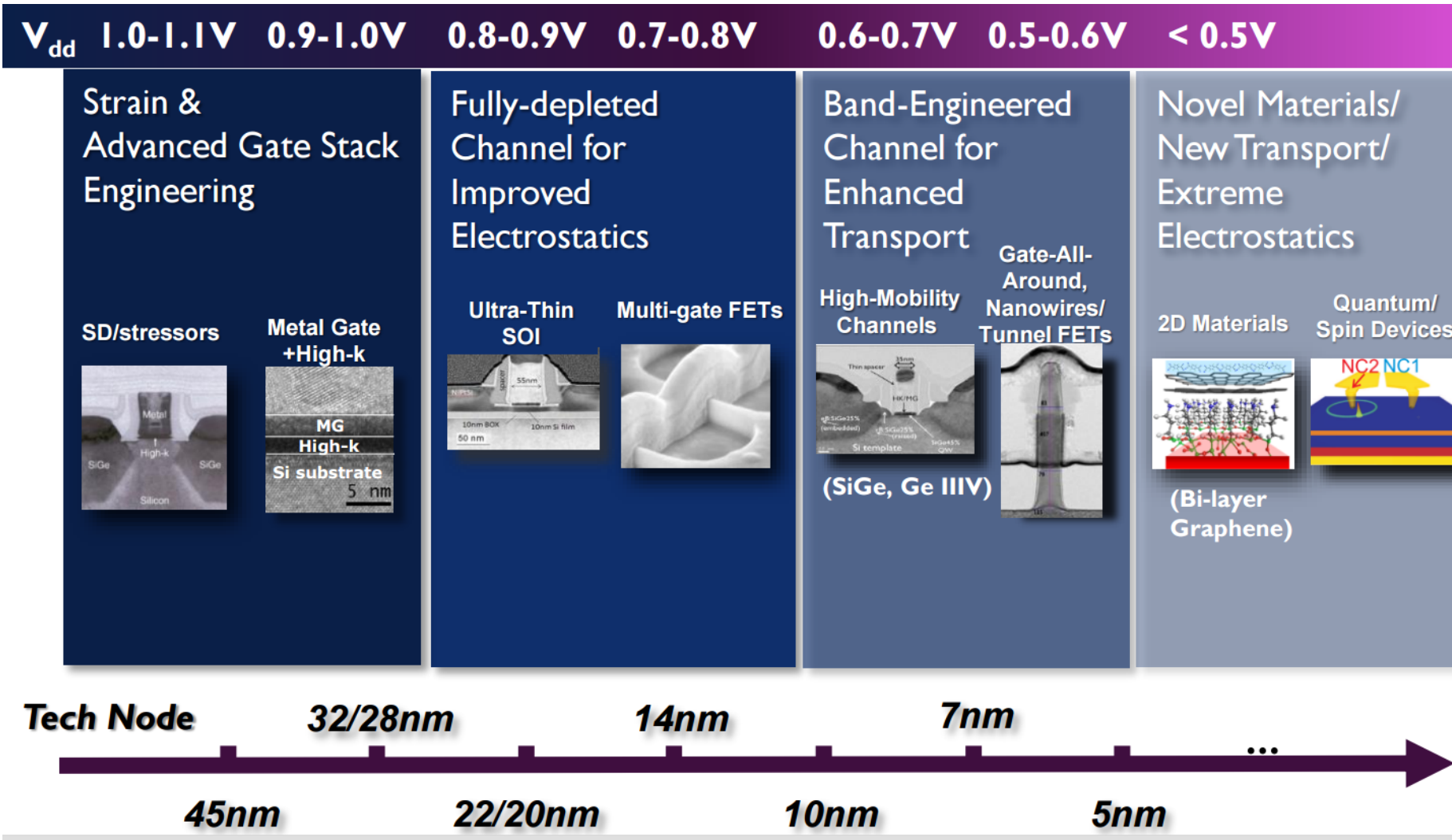


Main Enabler:

- Novel Design Concepts
- Novel Materials

Source: IMEC 2015

Transistors Technology Nodes- Miniaturization Trend

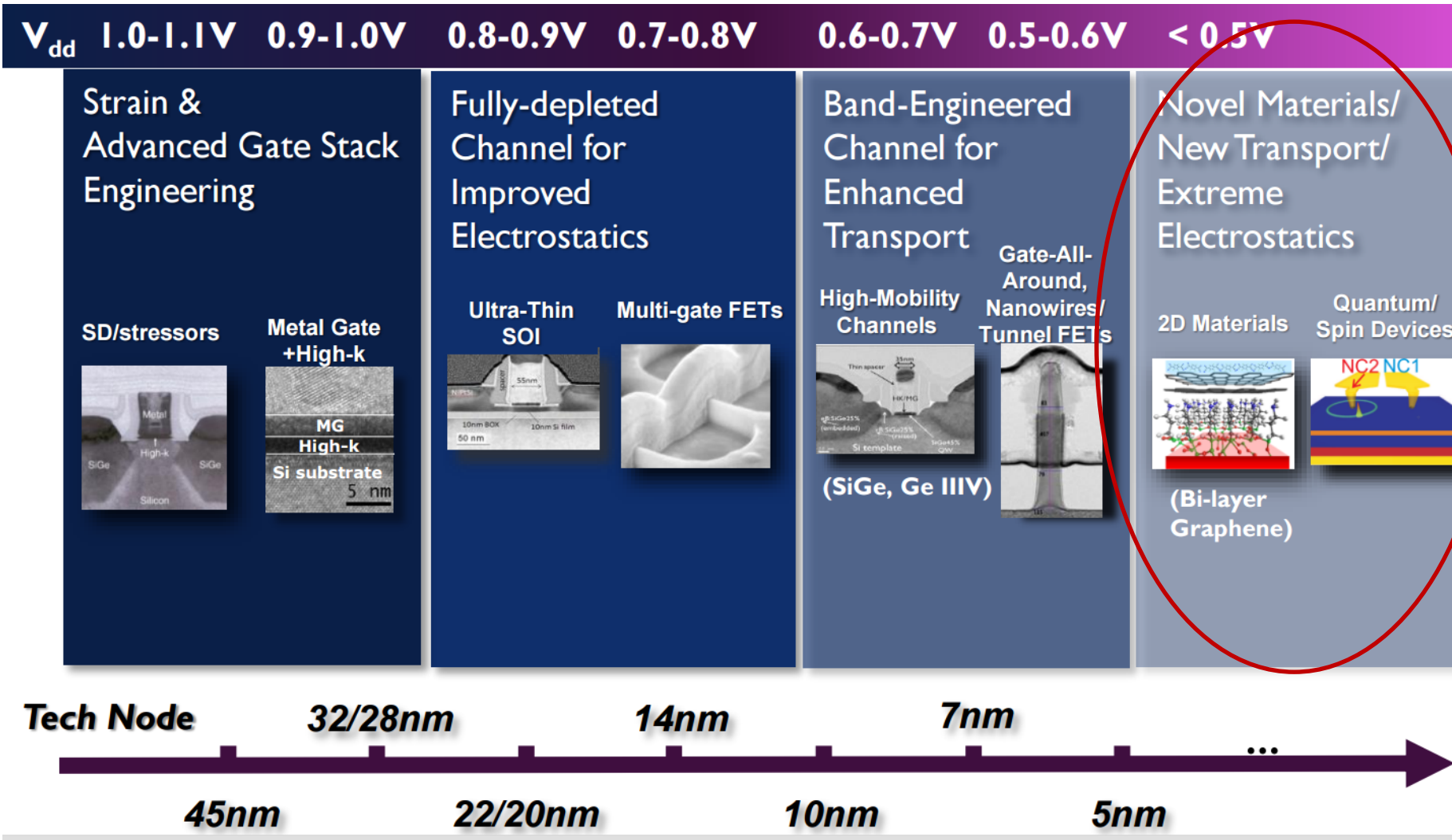


A whole team of:

- Engineers
- Physicists
- Material Scientists
- Chemists
- Biologists ...etc
- (Experimentalists and Theoreticians)

Source: IMEC 2015

Transistors Technology Nodes- Miniaturization Trend



A whole team of:

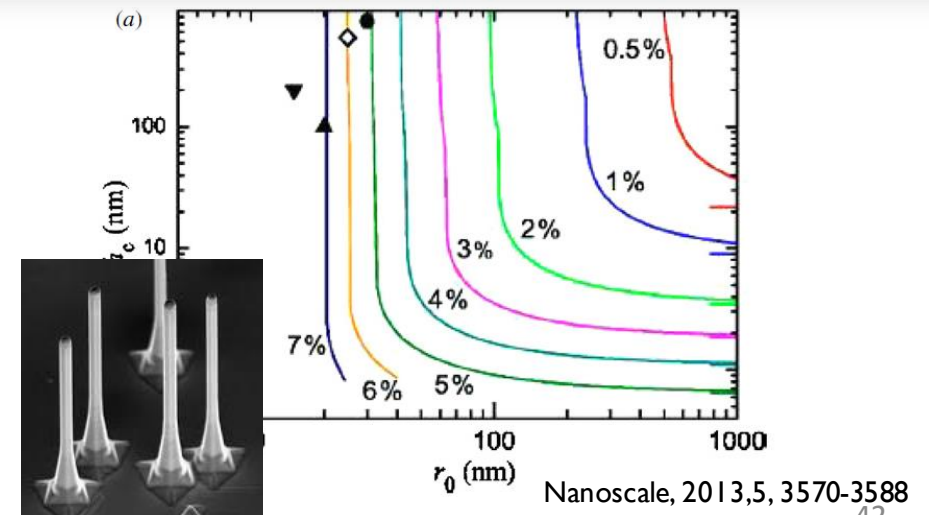
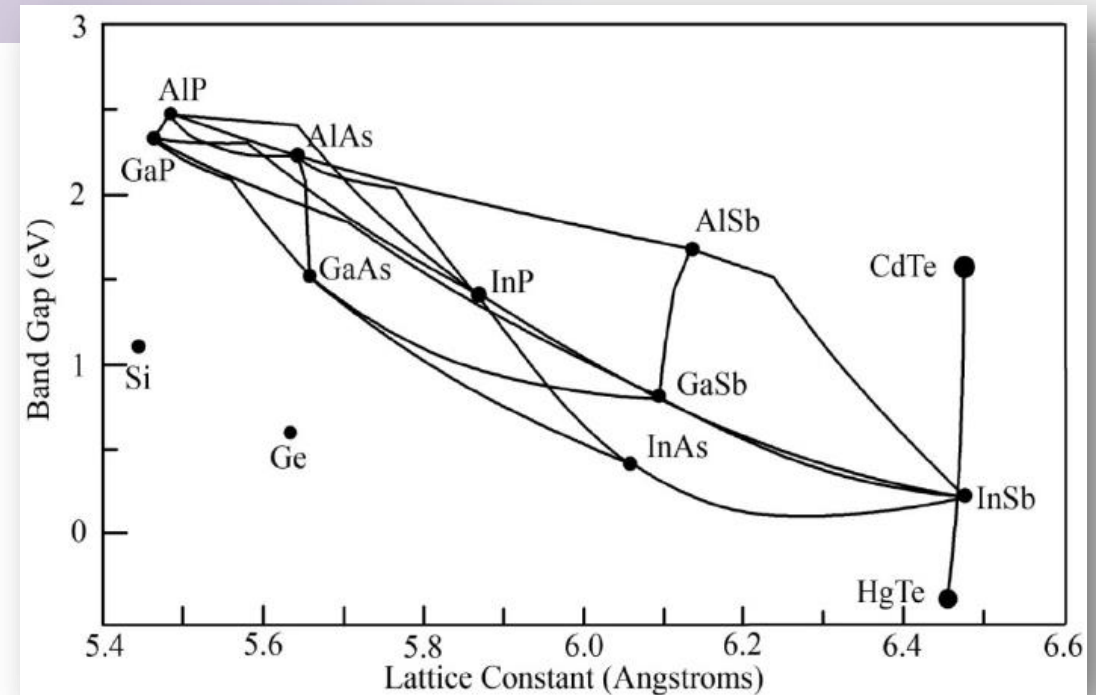
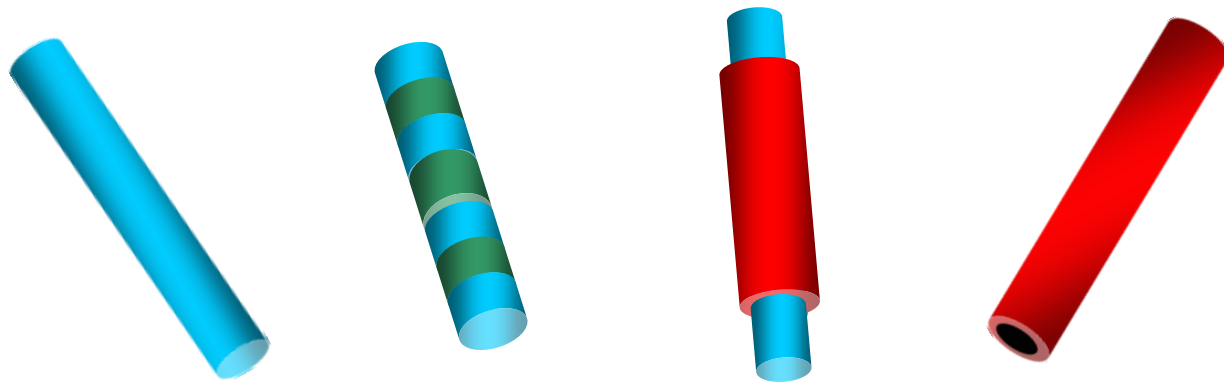
- Engineers
- Physicists
- Material Scientists
- Chemists
- Biologists ...etc
- (Experimentalists and Theoreticians)

Nanowires

Source: IMEC 2015

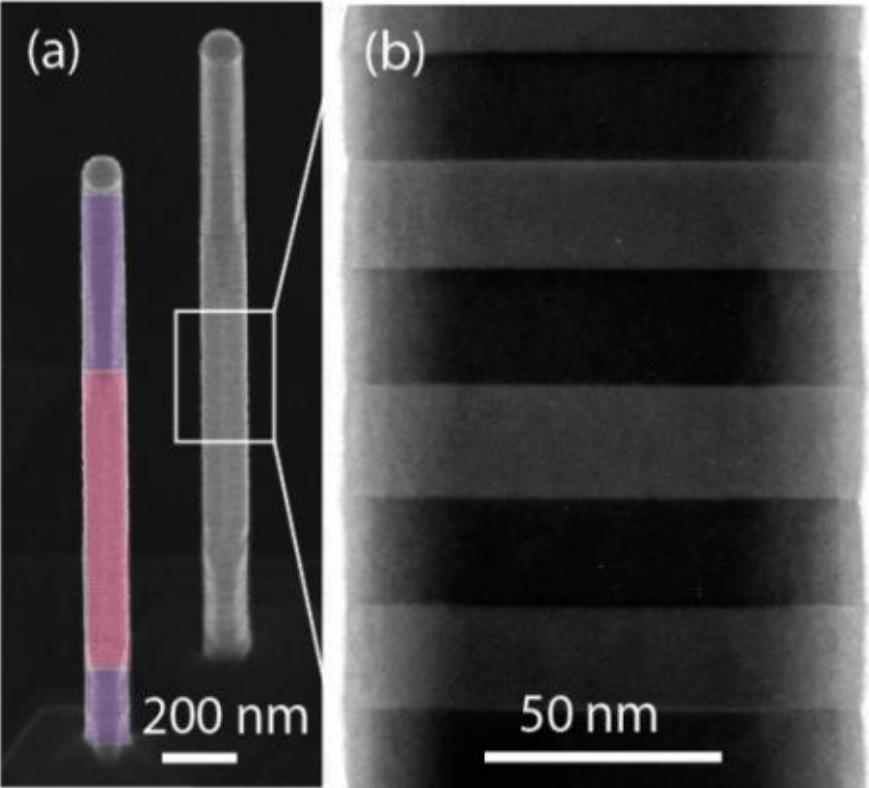
Why Nanowires?

- 1D geometry (**Quantum confinement**)
- Large Surface to volume ratio
- Accommodating greater elastic strain (**tolerance of lattice mismatch**).
- Growth in different configurations



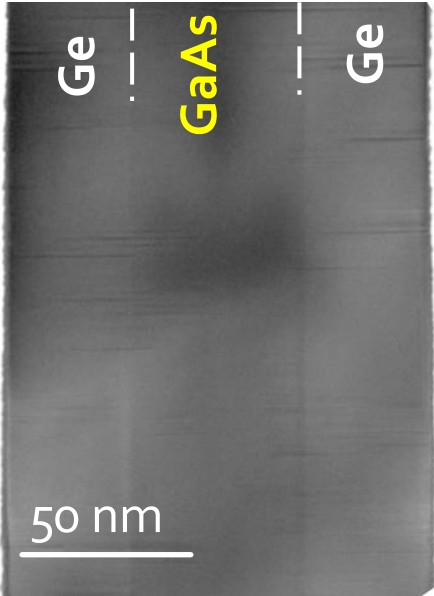
Freedom of Design of NWs

Axial Heterostructures (Quantum Barriers)

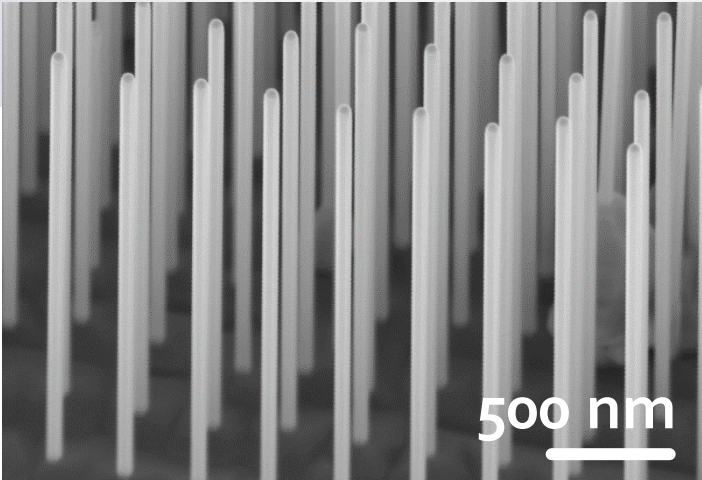


Nanotechnology, 2012, 23, 285601

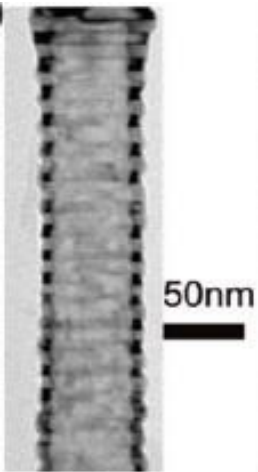
Radial Heterostructures Core/shell structures



Unpublished work

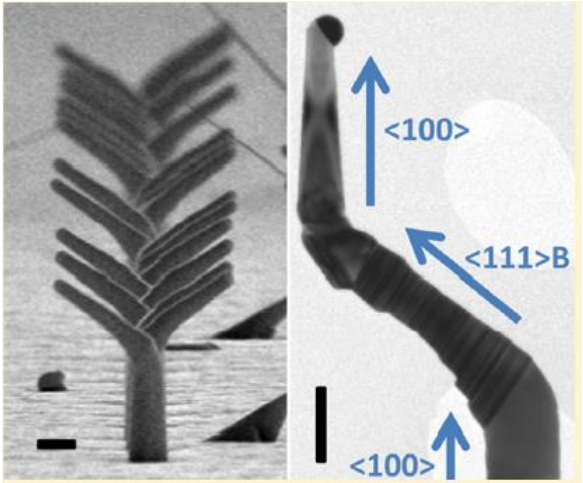
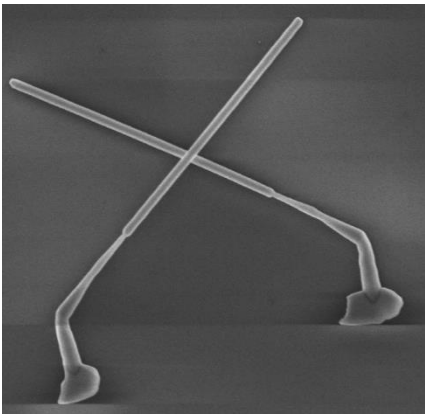


Hollow tubes

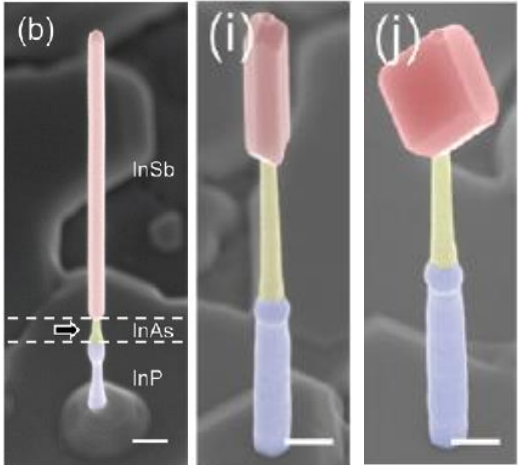


Nano Lett. 2011, 11, 1690–1694

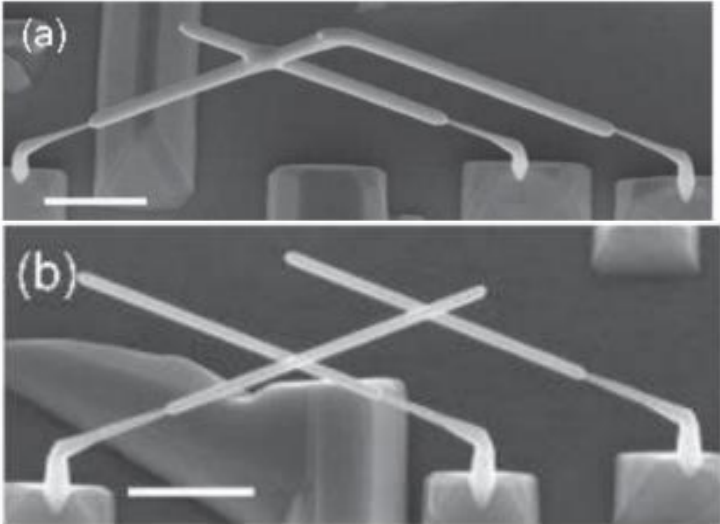
From 1D to 3D utilizing NWs



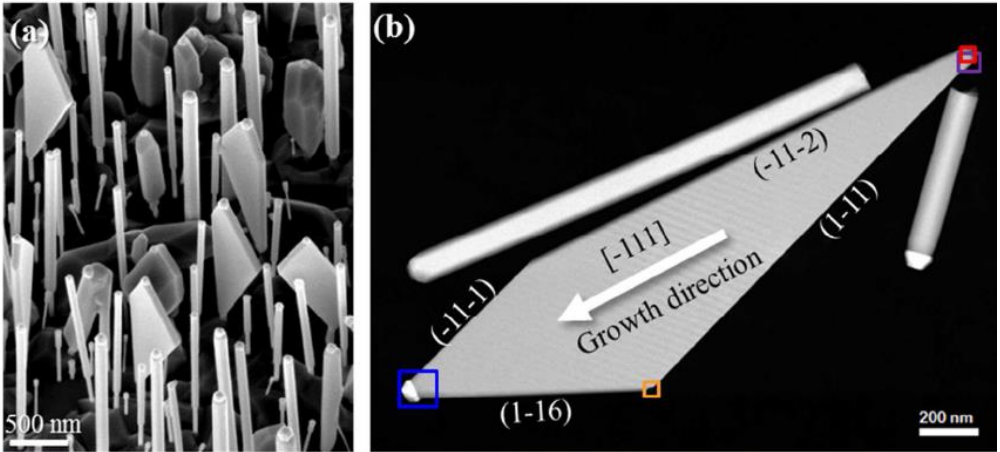
Nano Lett. 2013, 13, 3802–3806



Nano Lett. 2012, 12, 1794–1798



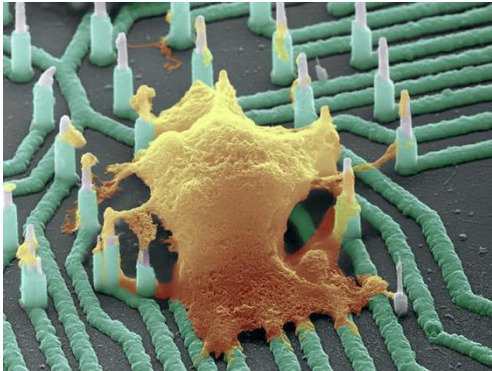
Adv. Mater. 2014, 26, 4875–4879



Nano Lett., 2016, 16 (2), pp 825–833.

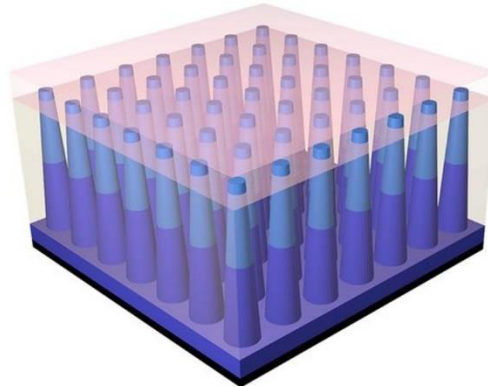
Nanowires Applications

Neurology / Brain Monitoring



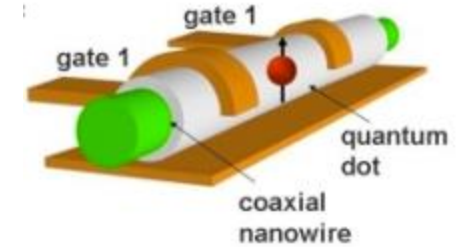
R. Liu et al., *Nano Lett.*, **2017**, 17 (5), pp 2757–2764

Light & Solar Cells



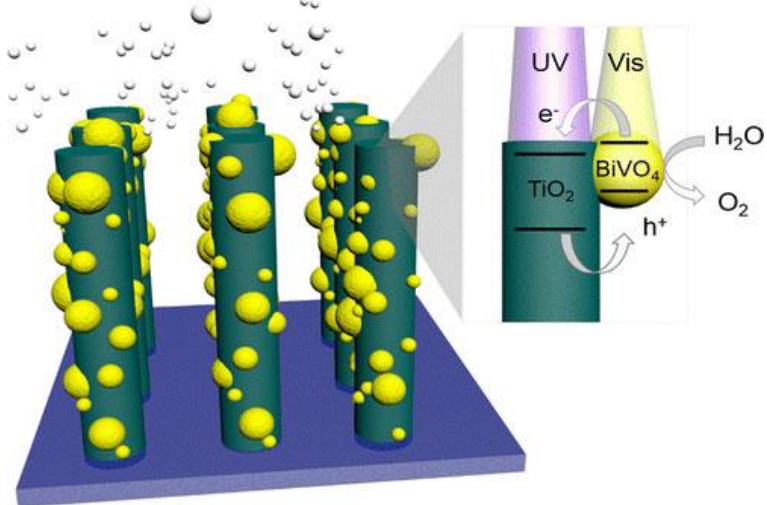
Y. Chao et al., *Nano Lett.*, **2013**, 13 (9), pp 4113–4117

Spintronics



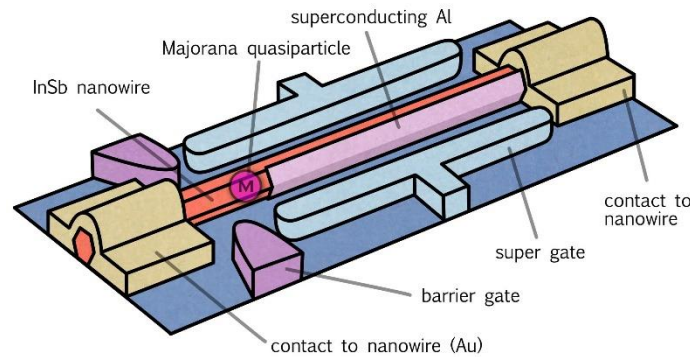
arXiv:cond-mat/0703520

Water Splitting



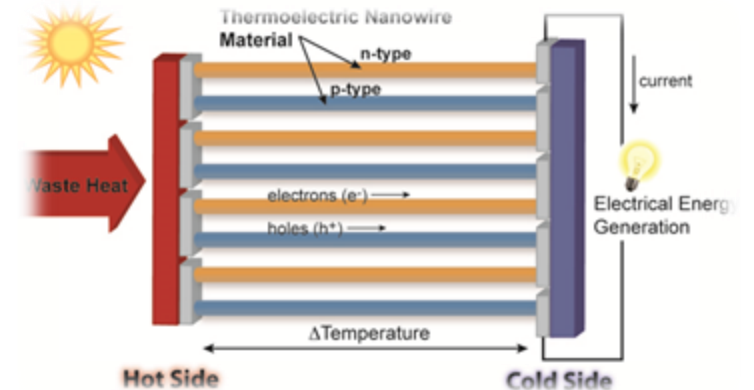
J. Resasco et al., *ACS Cent. Sci.*, **2016**, 2(2), pp 80–88

Quantum Applications



H. Zhang et al., *Nature* **volume556**, pages74–79 (05 April 2018)

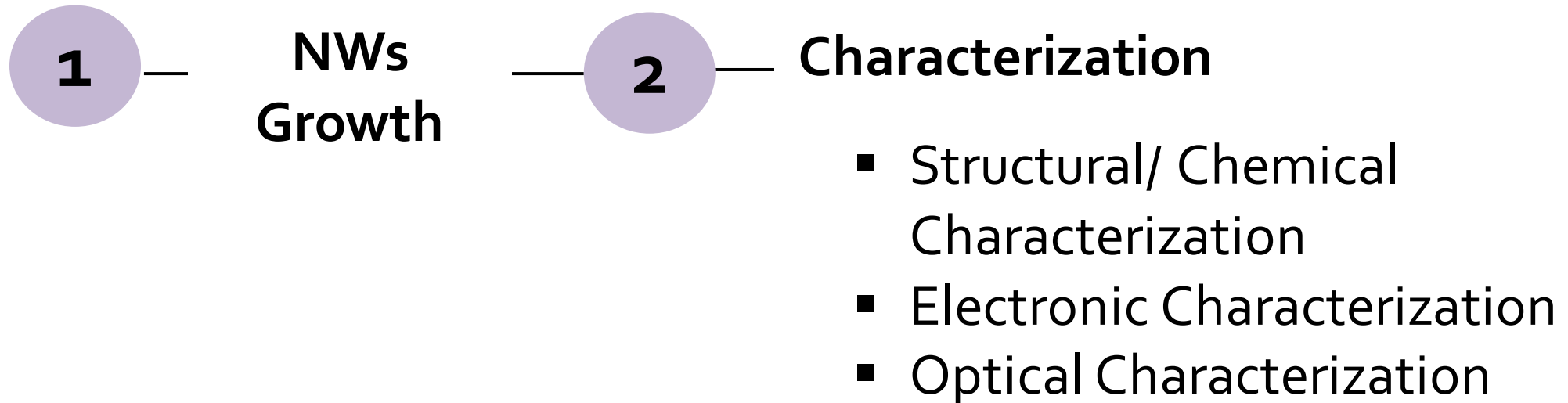
Thermoelectric devices



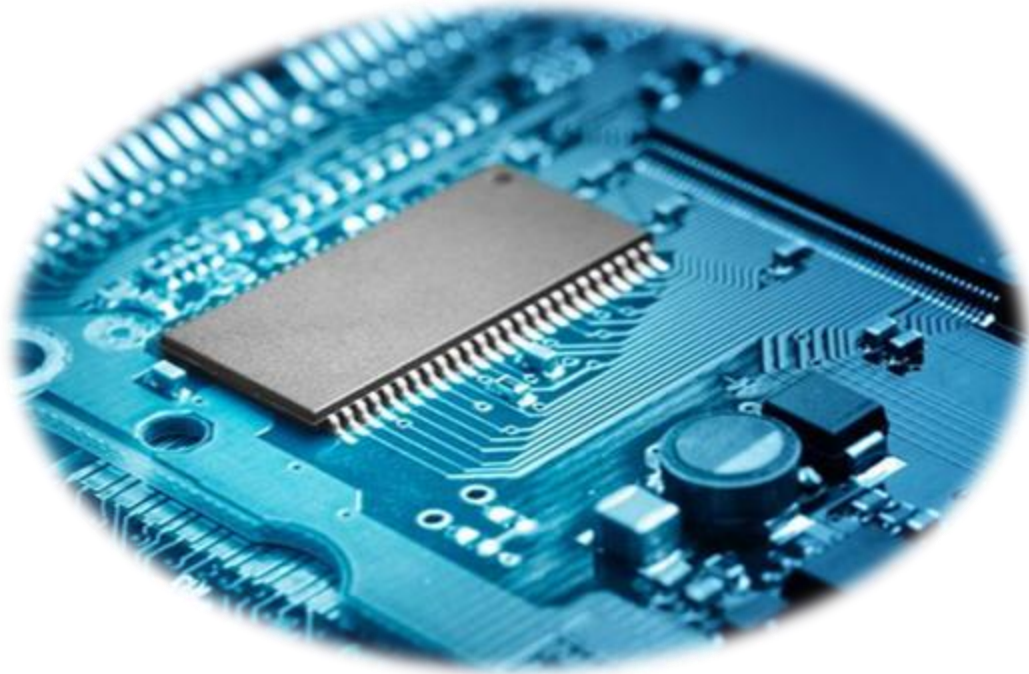
Niche of My Doctoral Research

The key objective is to unite the major advantages of design freedom offered by nanowires with the key properties of the chosen semiconductor Materials

2 examples of 2 research projects



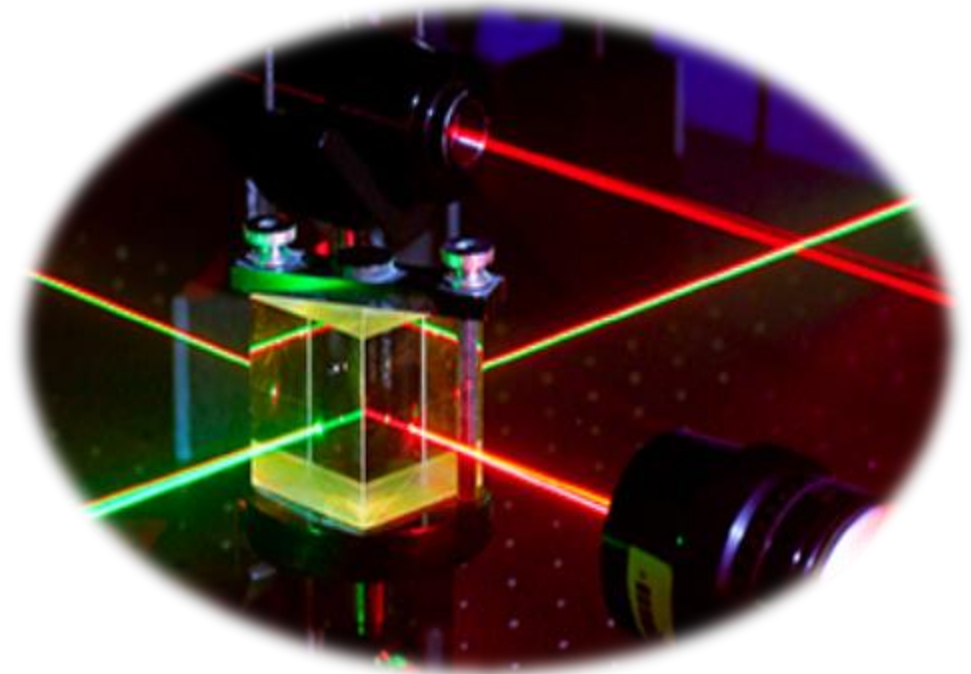
Example 2: Efficient Light Emission from Ge and SiGe



Electronics

Group IV: Si, Ge

Abundant Materials



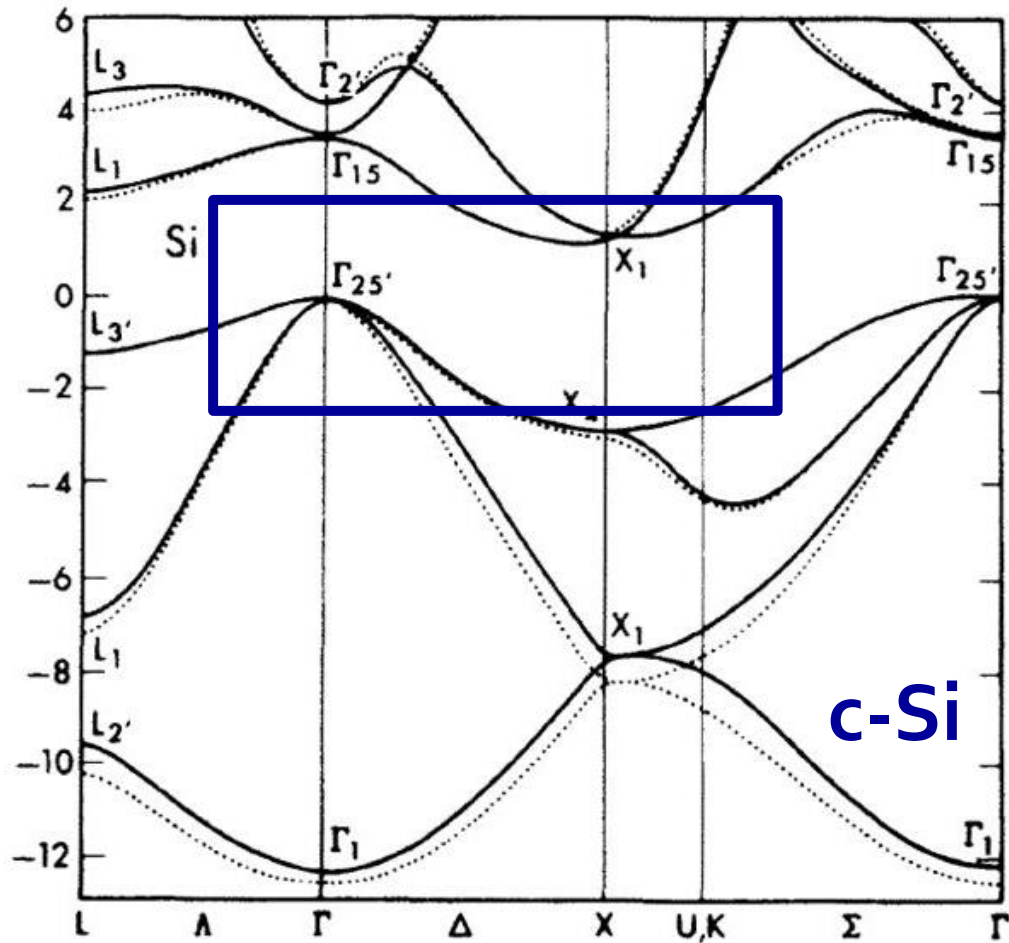
Optoelectronics

Group III-Vs: GaAs, InP, ...

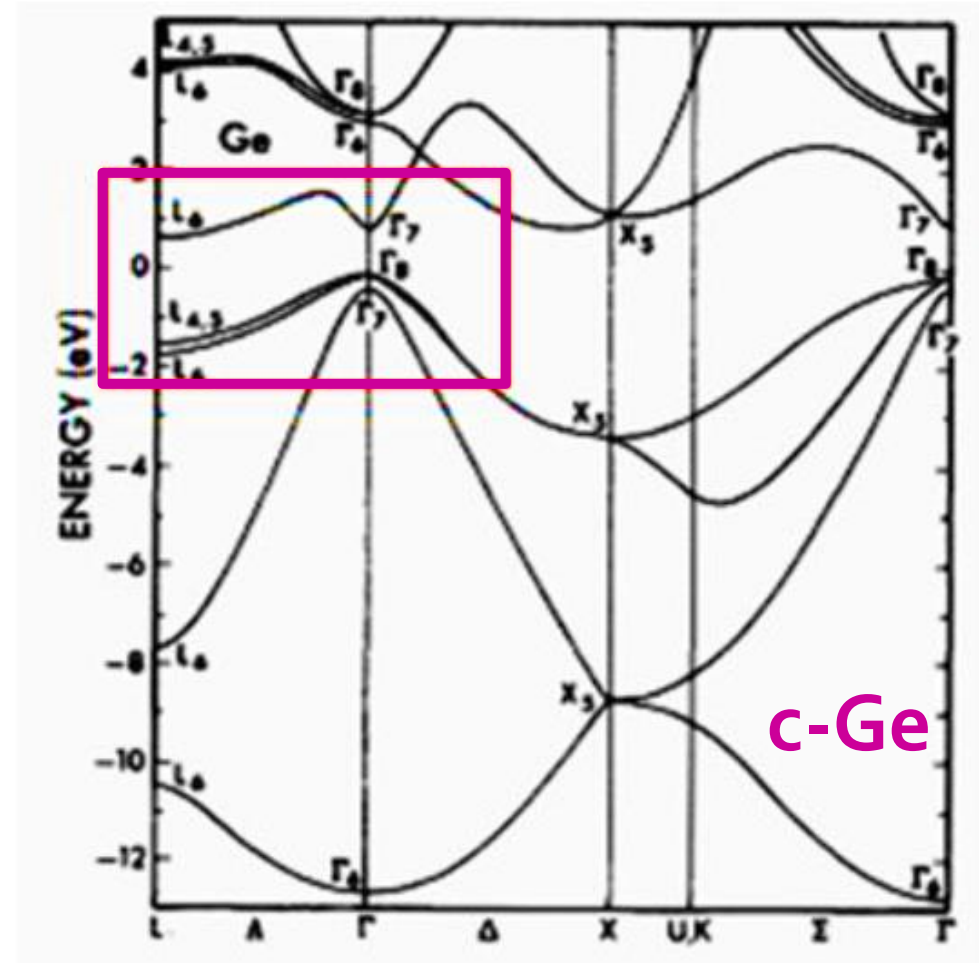
Expensive Materials

Band structure of cubic crystal structure

BUT cubic **Si** and **Ge** are indirect!

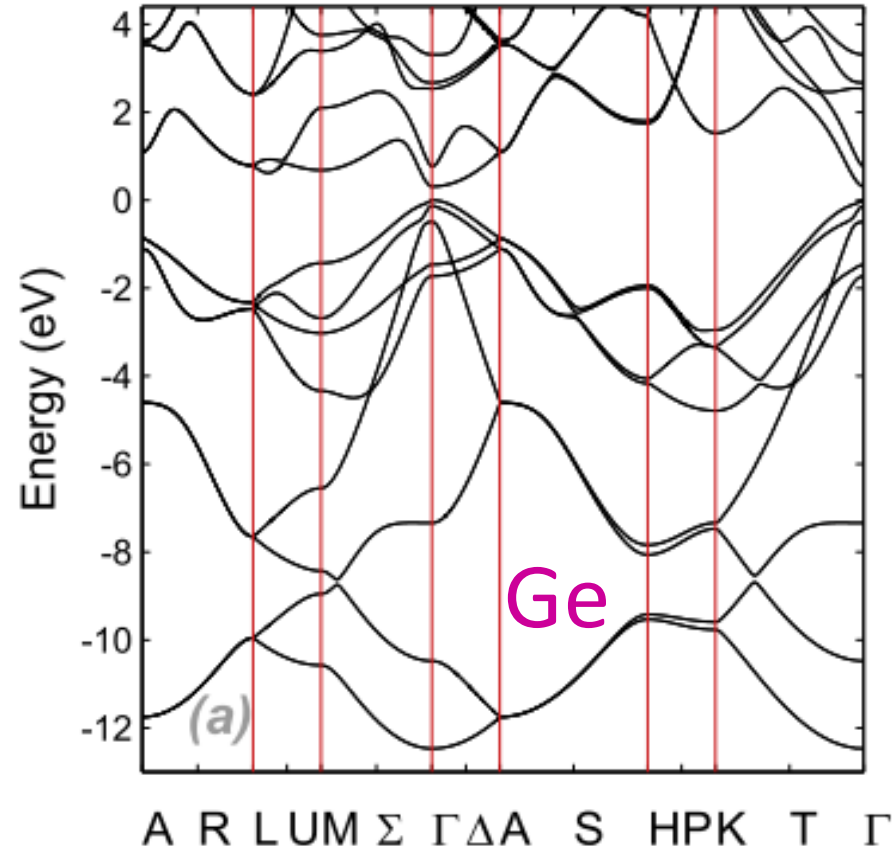
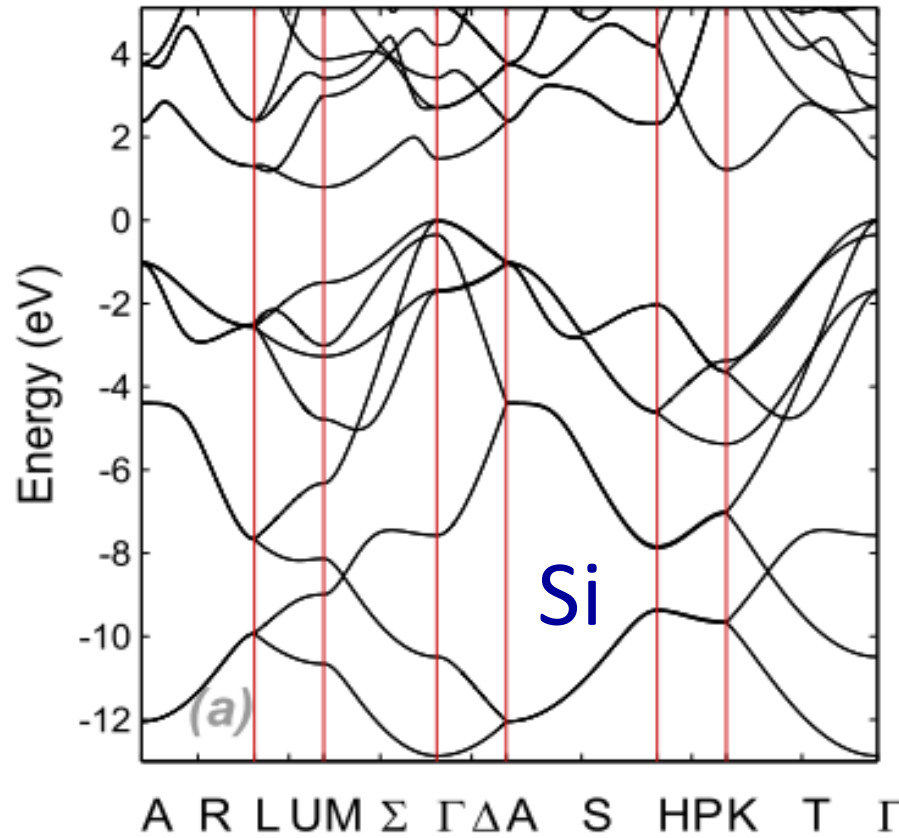


Wave vector (K)



Are Band structures of other crystal structures different?

Hexagonal Crystal Structure



C. Raffy et al., Phys. Rev. B: Condens. Matter Mater. Phys. **2002**, 66 (7), 075201

J. D. Joannopoulos et al., Phys. Rev. B **1973**, 7 (6), 2644–2657

A. De and C. E. Pryor, J. Phys.: Condens. Matter **2014**, 26 (4), 045801

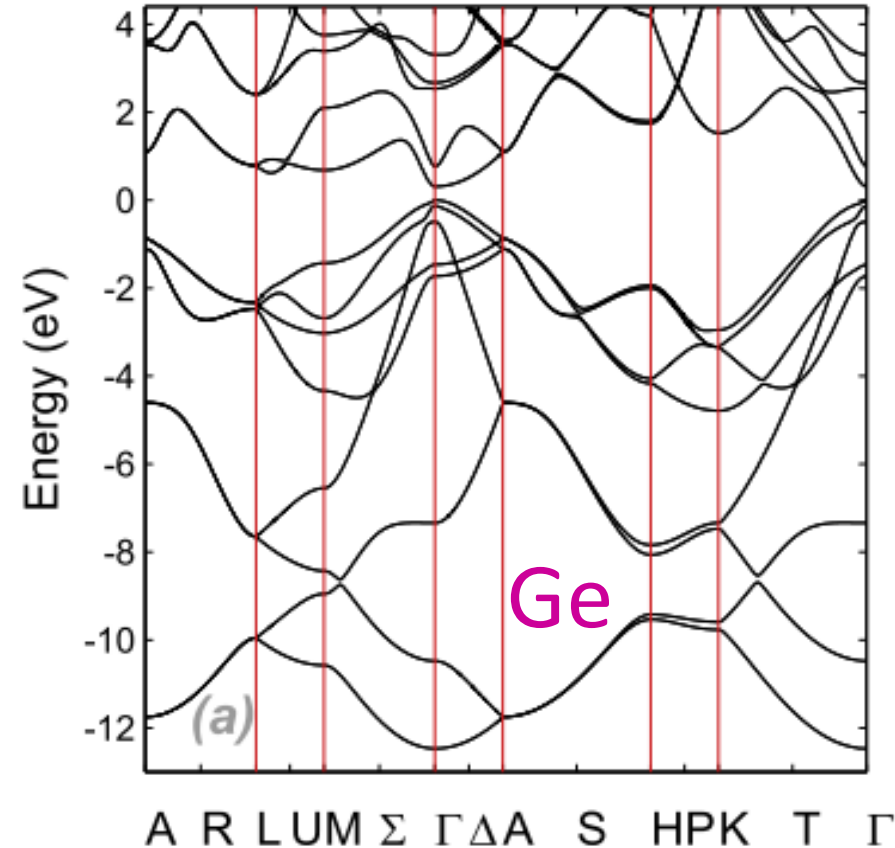
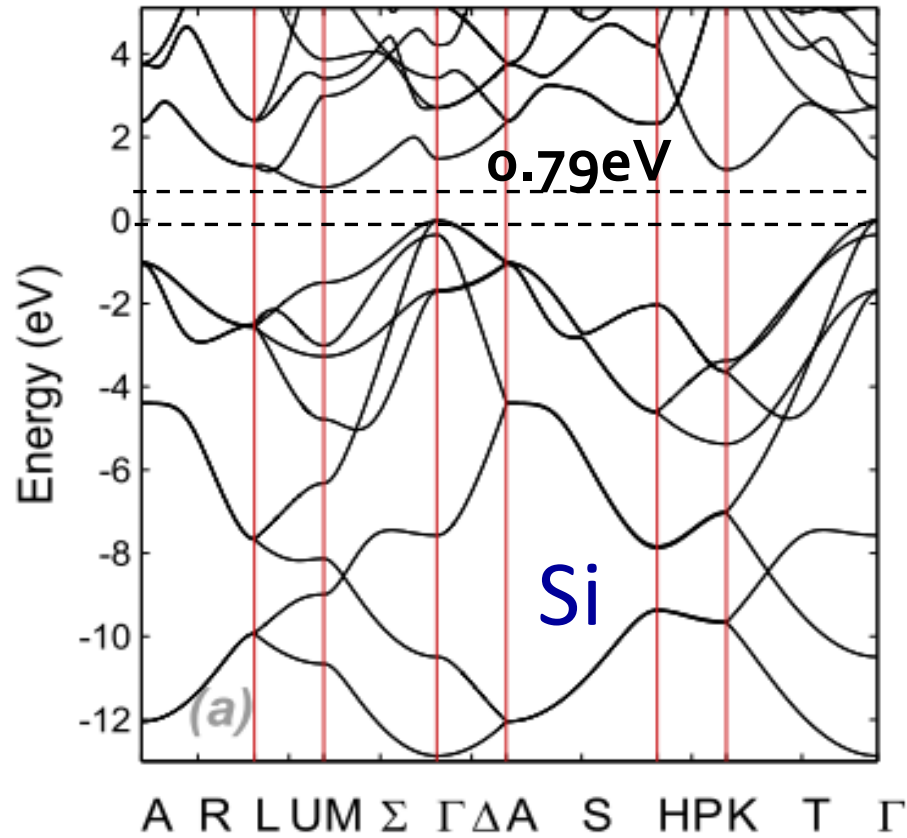
Q. Fan et al., Materials and Design **2017**, 132, 539–551

P. Chen et al., J. Phys. D: Appl. Phys. **2017** 50, 015107

X. Cartoixa et al., Nano Lett. **2017**, 17, 4753–4758

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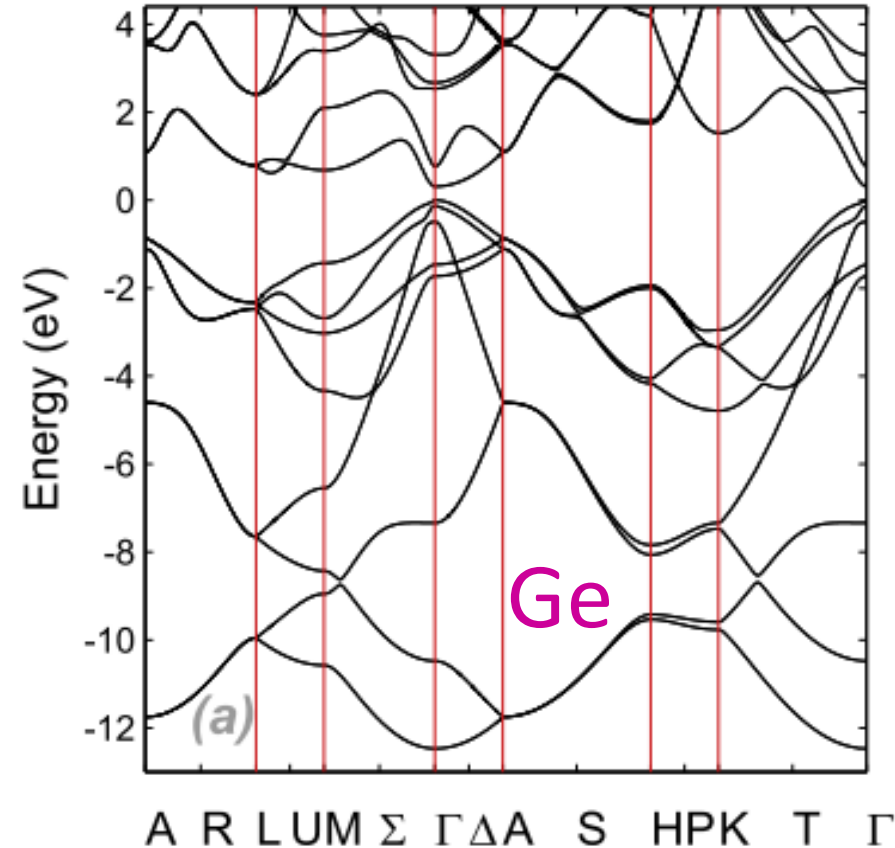
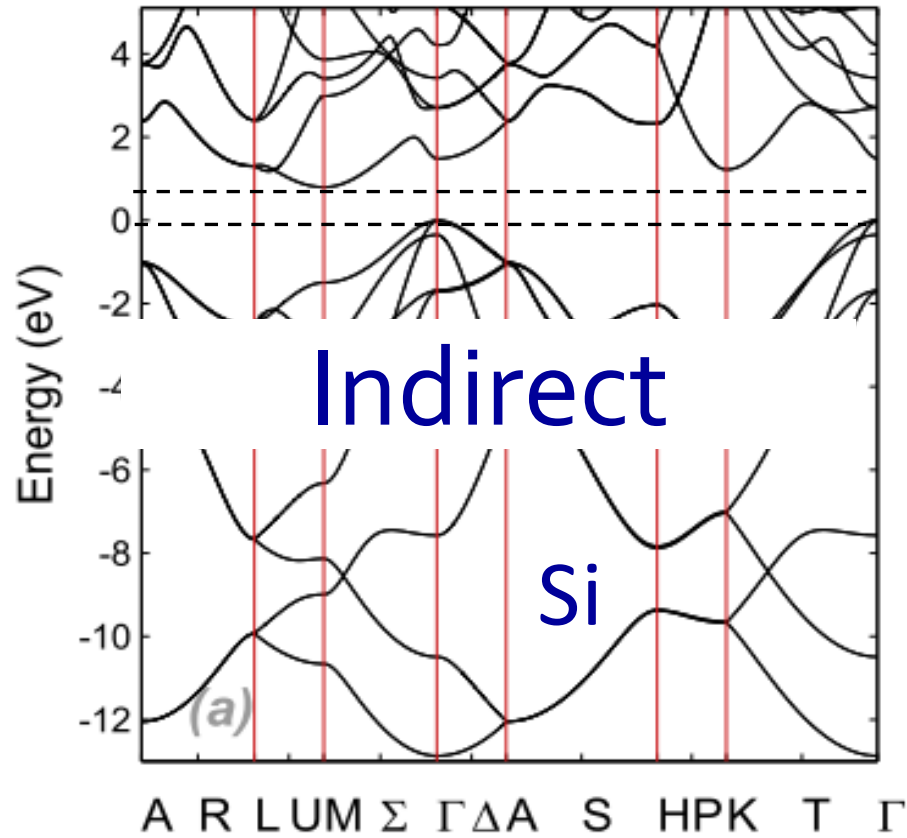
Q. Fan et al., Materials and Design **2017**, 132, 539–551

P. Chen et al., J. Phys. D: Appl. Phys. **2017** 50, 015107

X. Cartoixa et al., Nano Lett. **2017**, 17, 4753–4758

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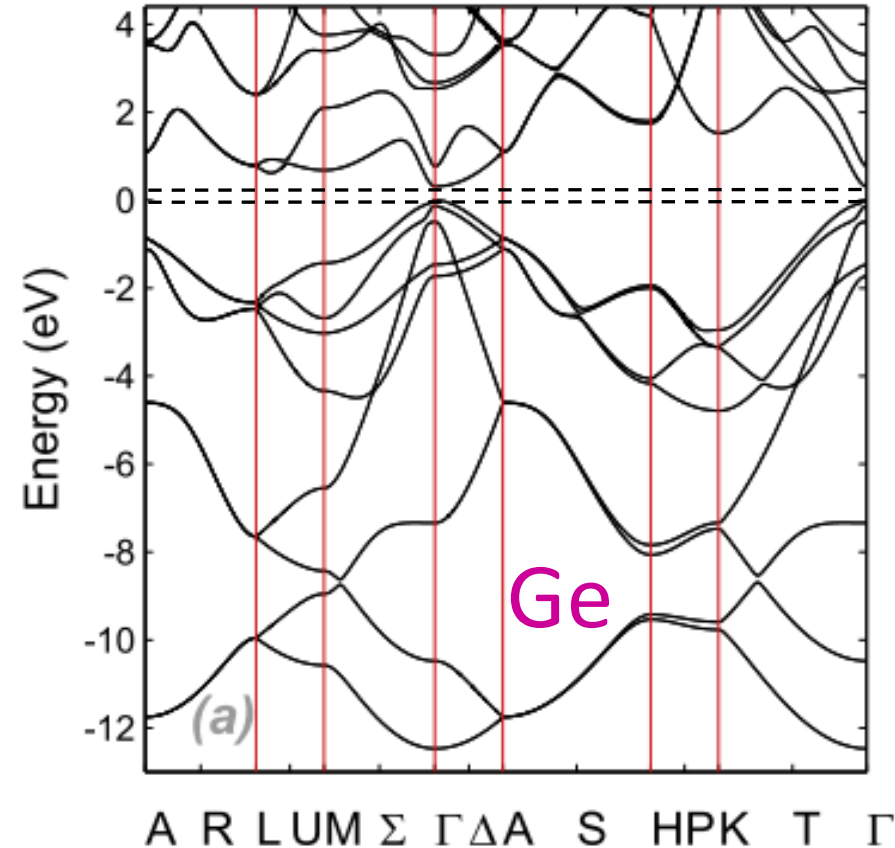
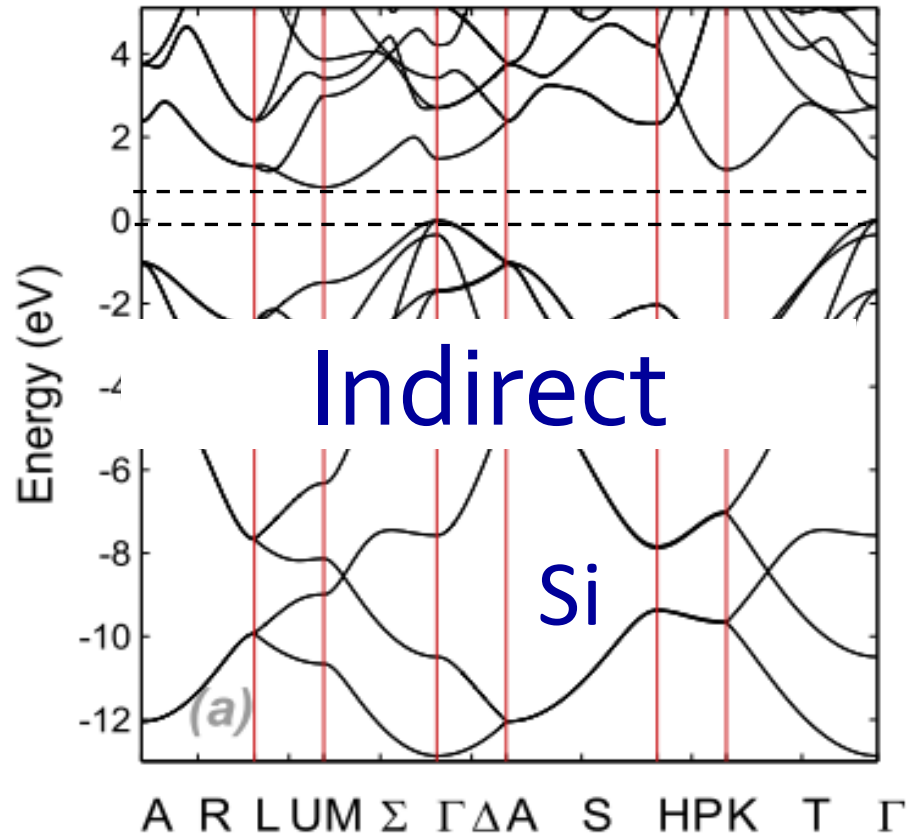
Q. Fan et al., Materials and Design **2017**, 132, 539–551

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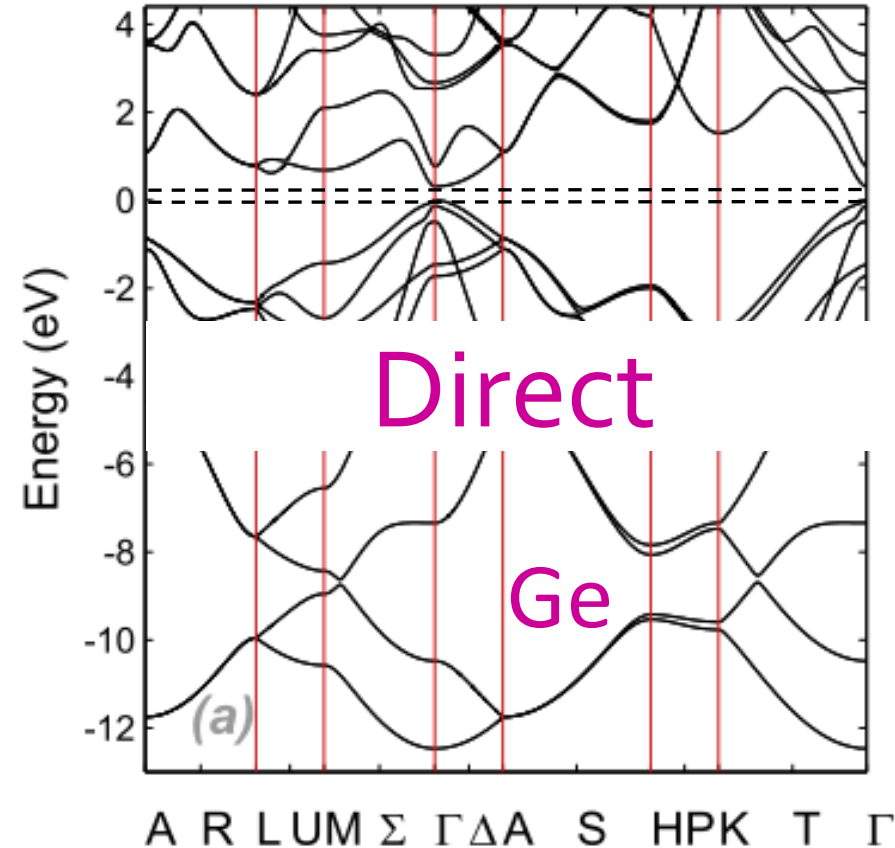
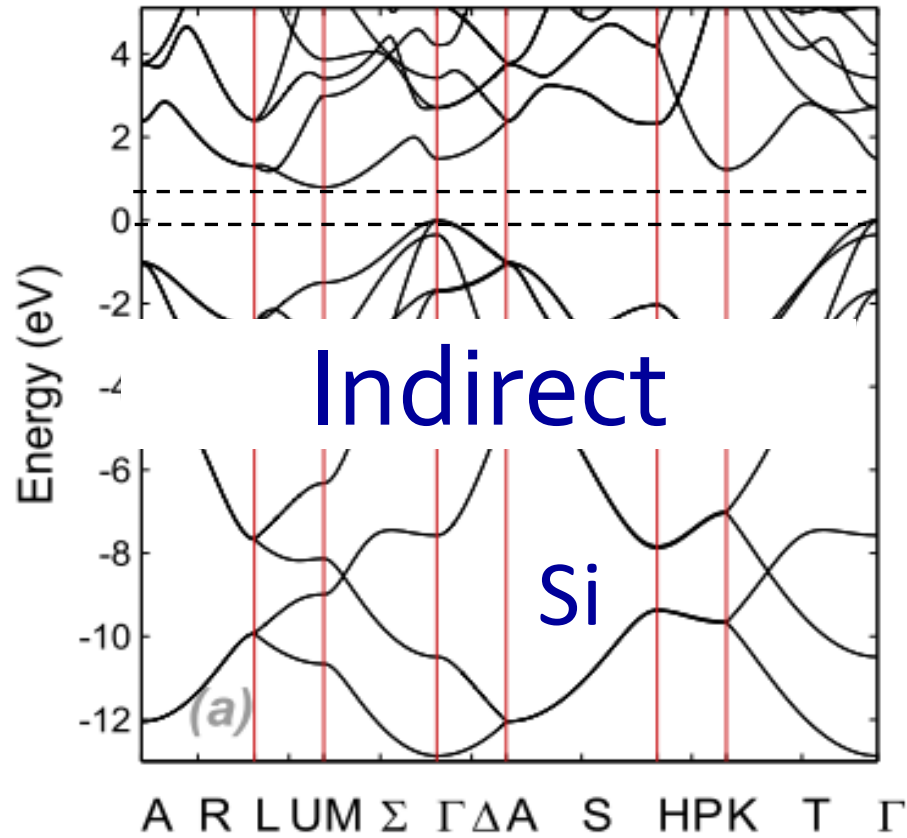
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J. D. Joannopoulos et al., Phys. Rev. B **1973**, 7 (6), 2644–2657

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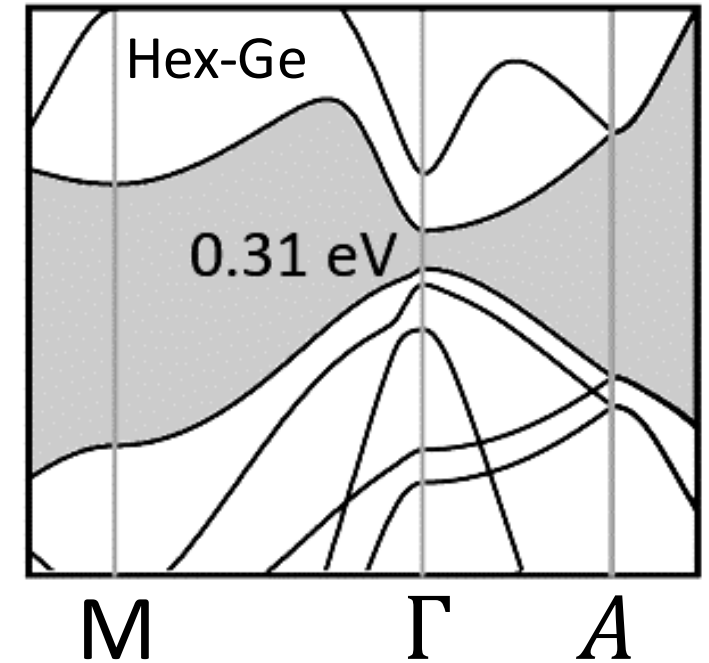
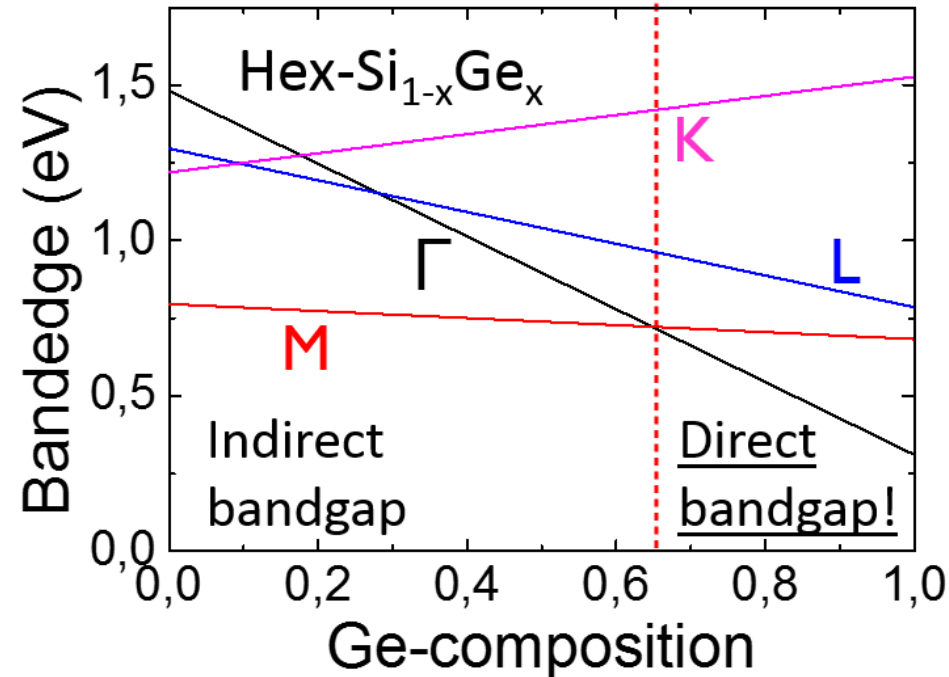
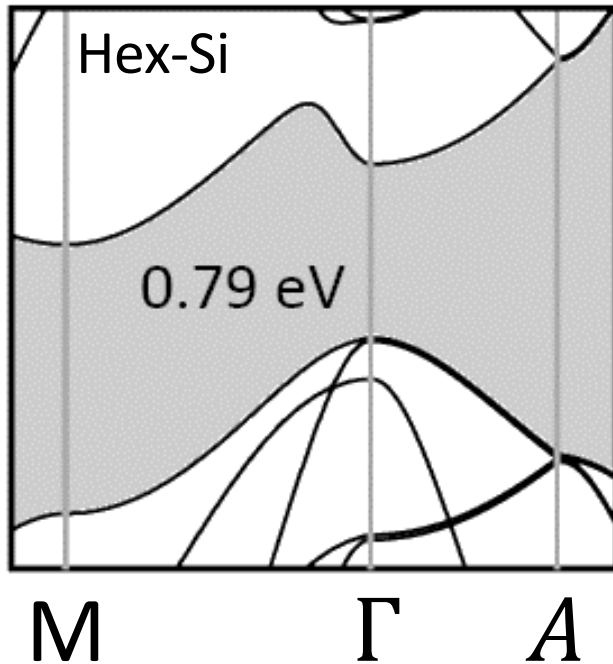
Q. Fan et al., Materials and Design **2017**, 132, 539–551

P. Chen et al., J. Phys. D: Appl. Phys. **2017** 50, 015107

X. Cartoixa et al., Nano Lett. **2017**, 17, 4753–4758

Tunable direct bandgap of hexagonal $\text{Si}_x\text{Ge}_{1-x}$

*First order approximation

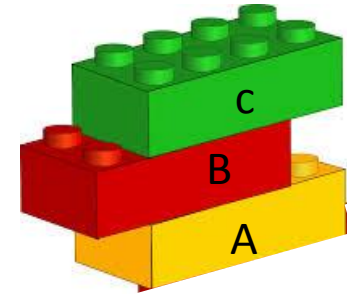
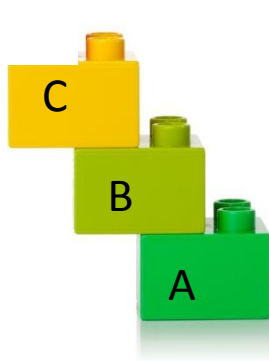


- Ge and Ge-rich SiGe (Ge > 60%) alloys are of direct bandgap nature!

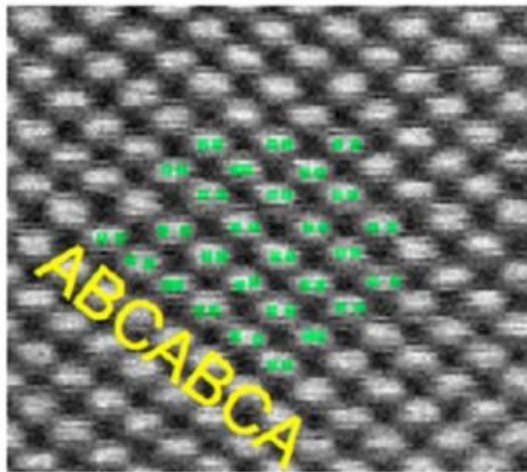
Hexagonal Ge Crystal Phase

BUT Ge naturally crystallizes in cubic phase

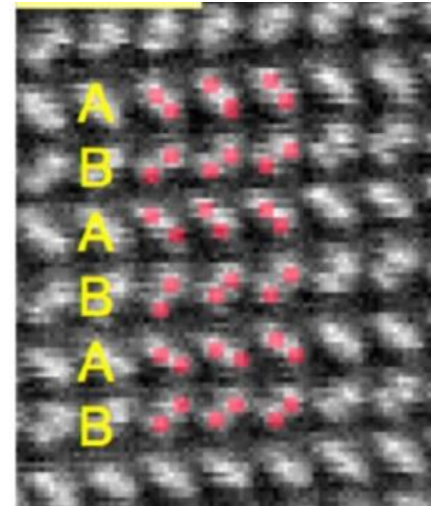
Crystal Structures- LEGO Analogy



Atomic stacking



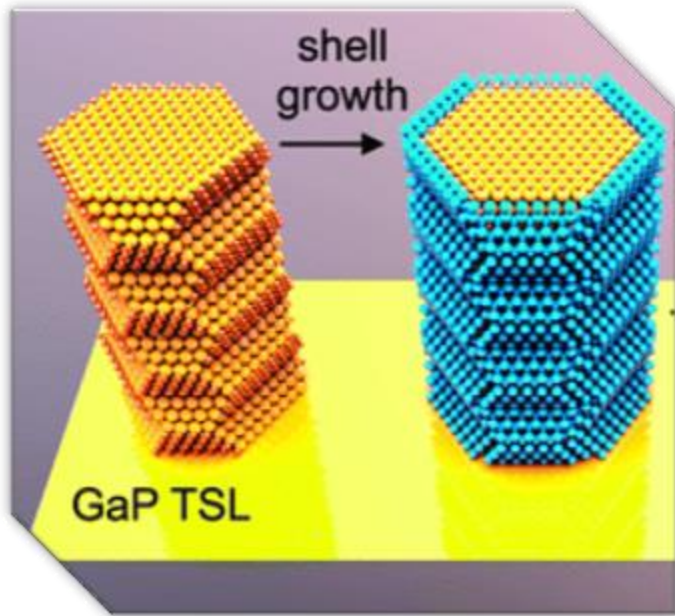
Typical cubic structure



Typical Wurtzite(WZ)
(hexagonal) structure

Experimental Realization of Hex-Si/Ge

Crystal transfer



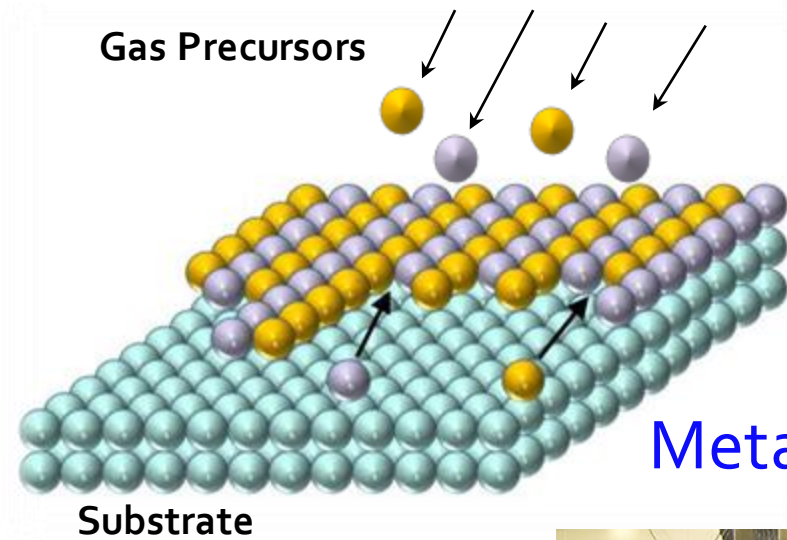
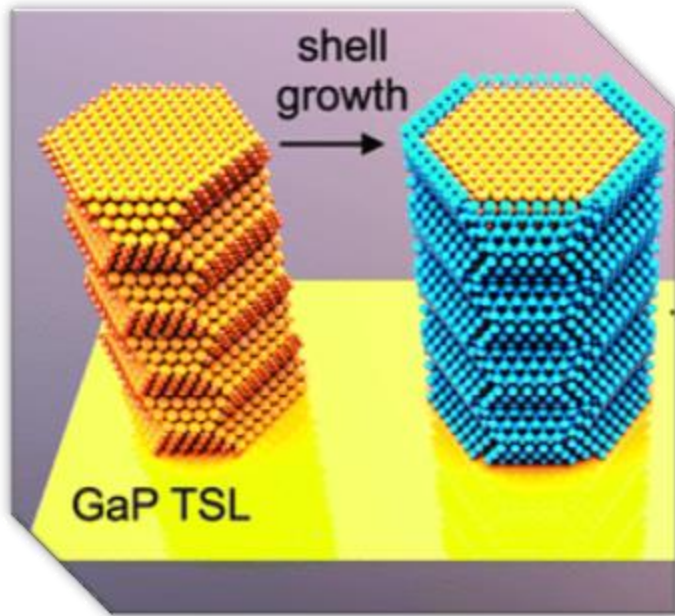
R. Algra et al., Nano Lett., 2011, 11, 1690–1694

Hauge et al., Nano Lett. 2015, 15, 5855–5860

Hauge et al., Nano Lett. 2017, 17, 85–90

Epitaxy of Materials

Crystal transfer



MOVPE
Metal Organic Vapor Phase Epitaxy

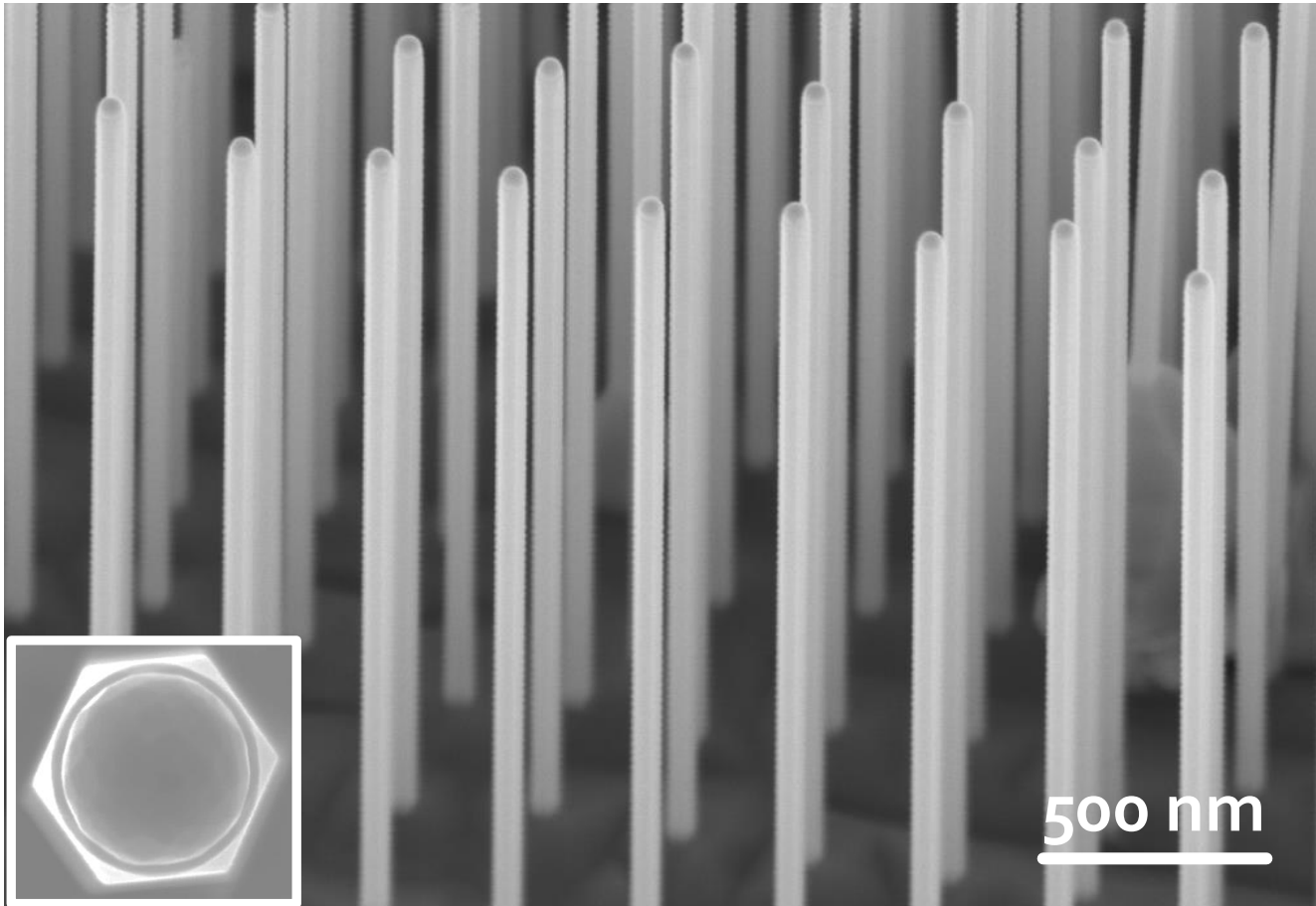
R. Algra et al., *Nano Lett.*, **2011**, *11*, 1690–1694

Hauge et al., *Nano Lett.* **2015**, *15*, 5855–5860

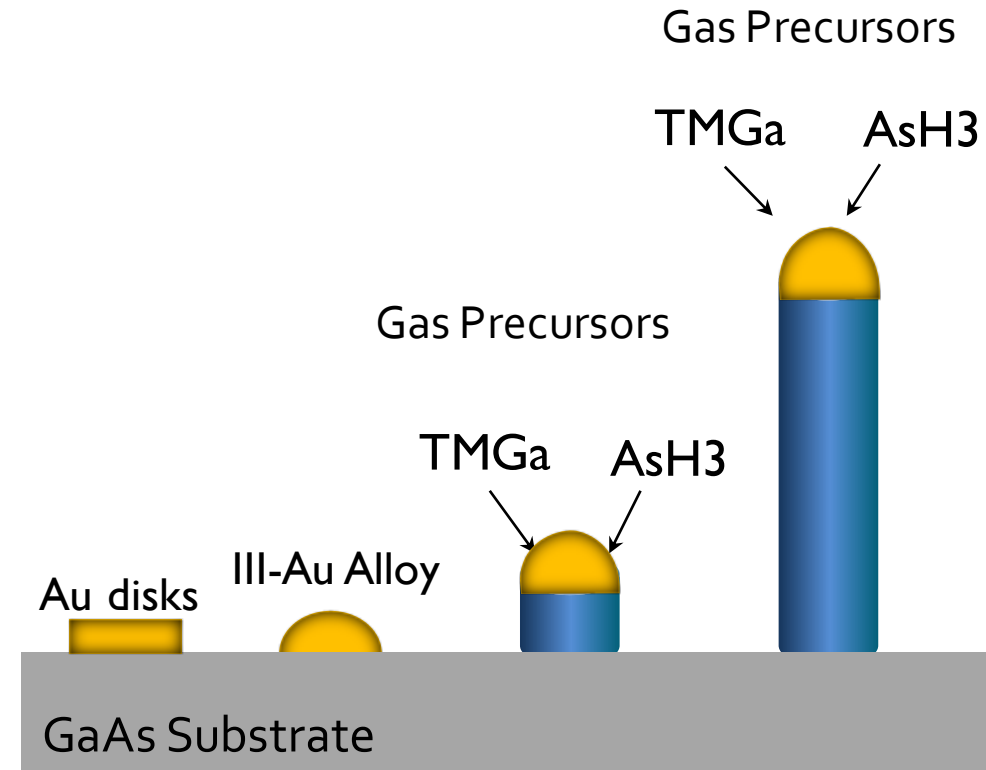
Hauge et al., *Nano Lett.* **2017**, *17*, 85–90



MOVPE Growth of WZ- GaAs Core NWs

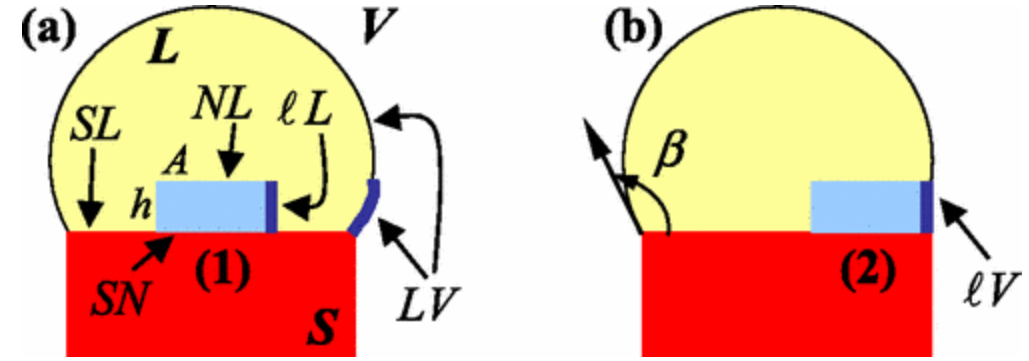
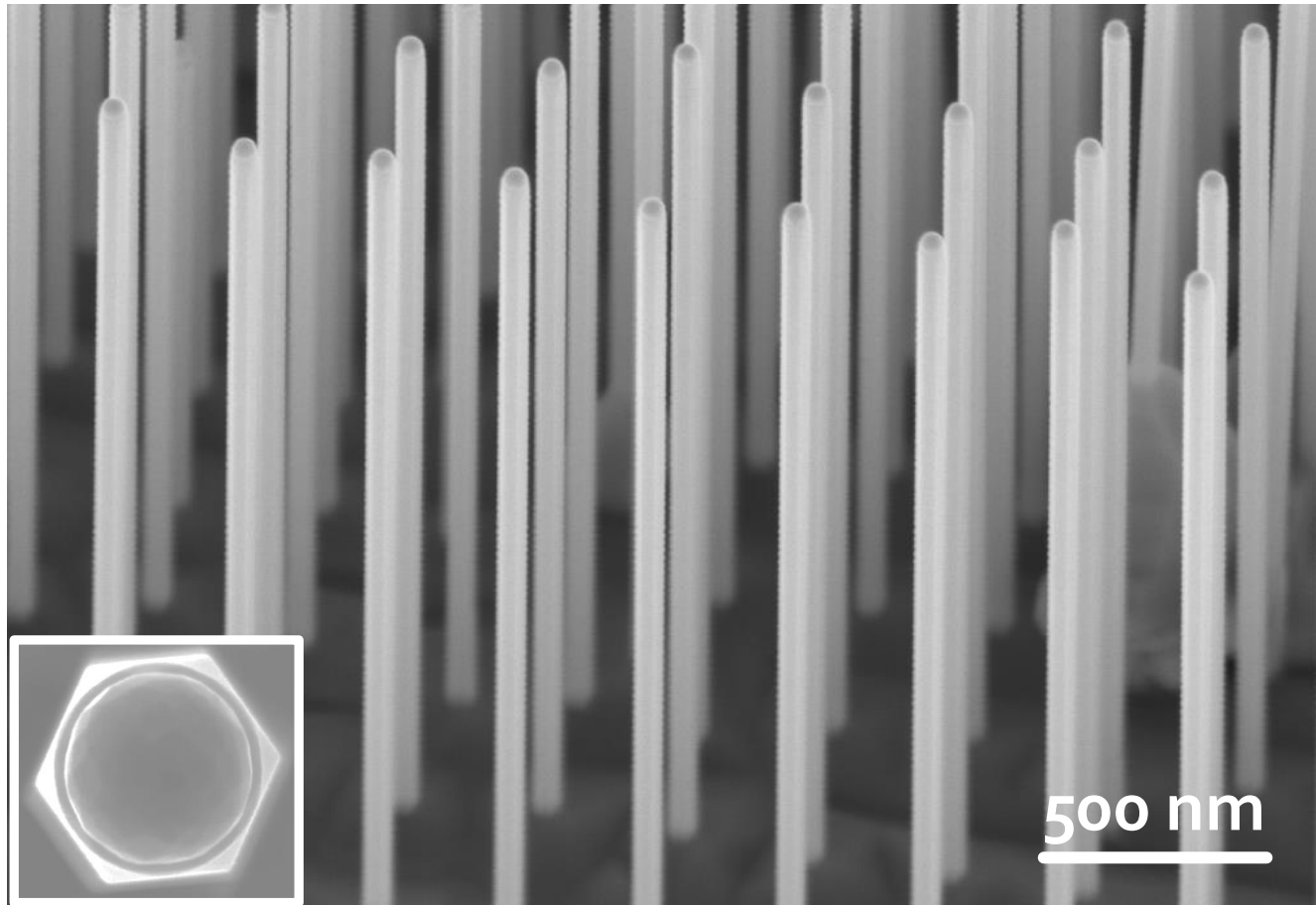


EBL Lithography defined Au-Catalyzed NWs



VLS- MOVPE

MOVPE Growth of WZ- GaAs Core NWs

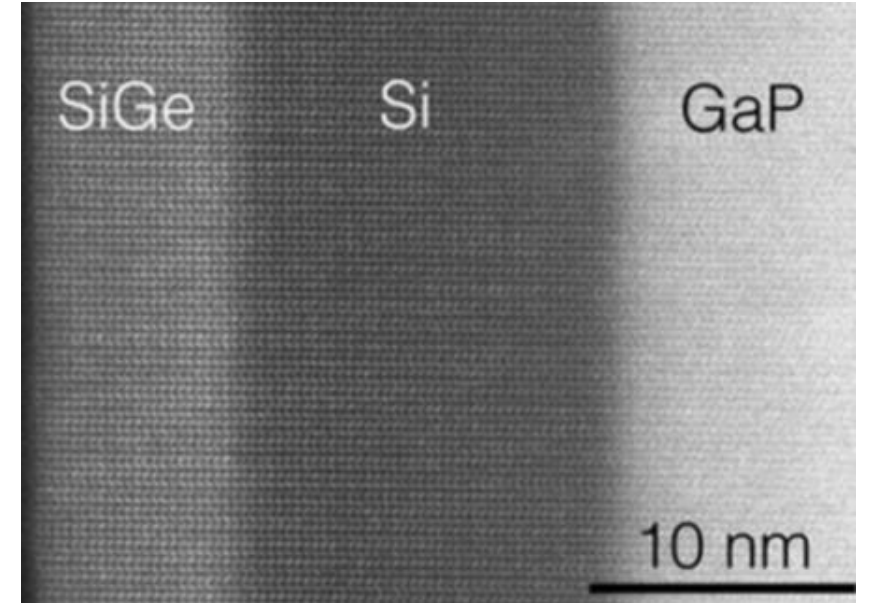
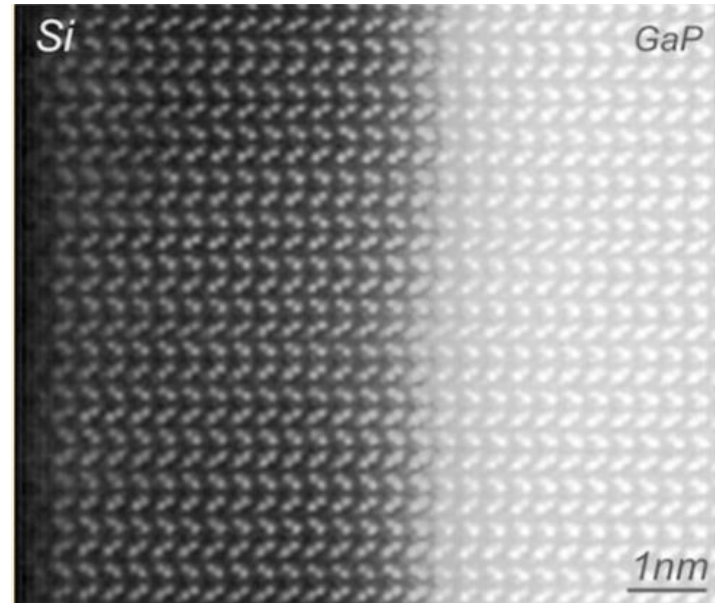
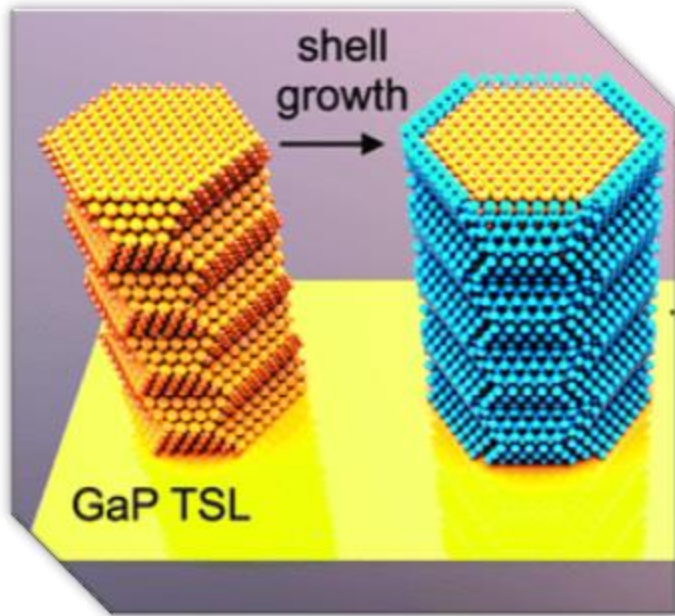


Thermodynamics of Vapor-Liquid-Solid Interfaces

EBL Lithography defined Au-Catalyzed NWs

Experimental Realization of Hex-Si/Ge

Crystal transfer



R.Algra et al., *Nano Lett.*, **2011**, *11*, 1690–1694
Hauge et al., *Nano Lett.* **2015**, *15*, 5855–5860
Hauge et al., *Nano Lett.* **2017**, *17*, 85–90

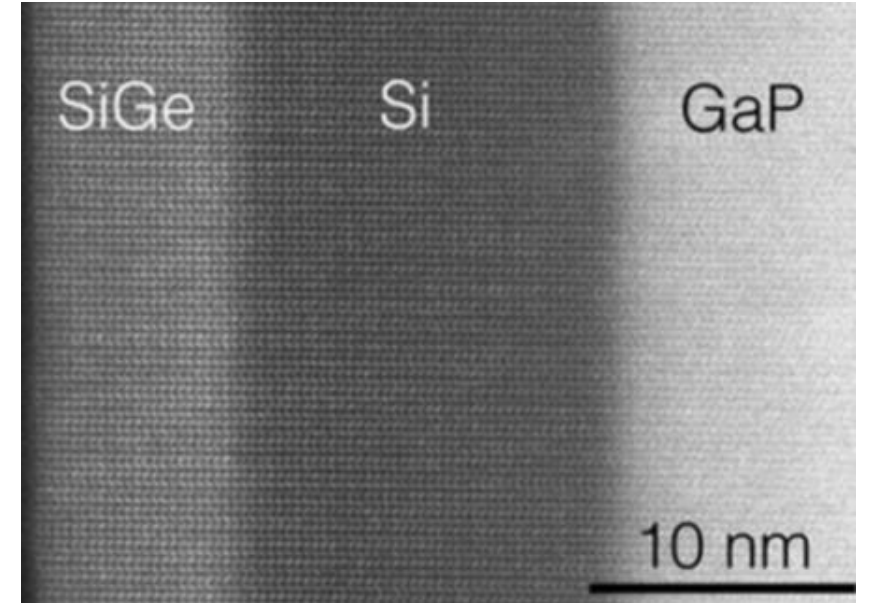
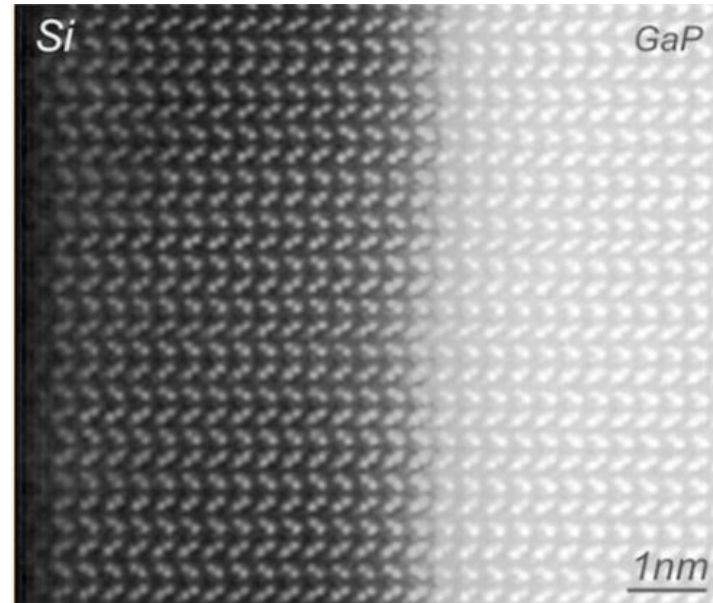
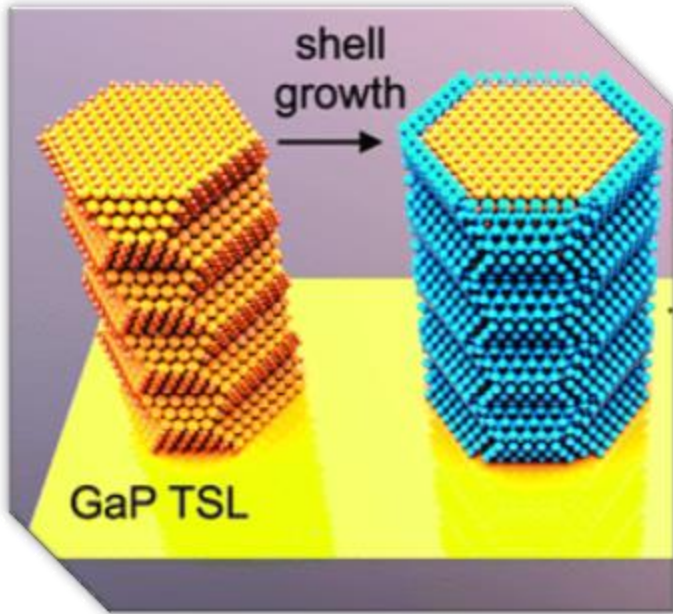
Parameters to vary:

- ✓ Temperature
- ✓ Precursor Gas Flows (Partial Pressures)
- ✓ Reactor Pressure
- ✓ Time

EDX Compositional Maps

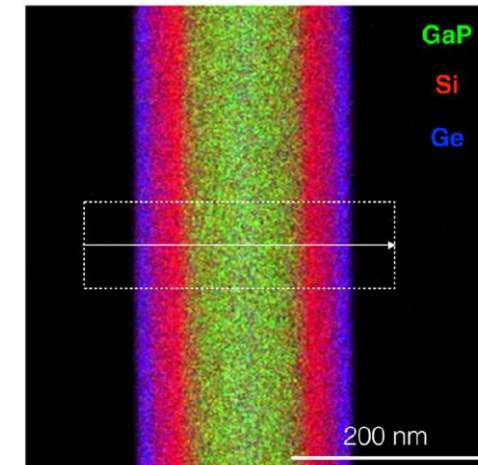
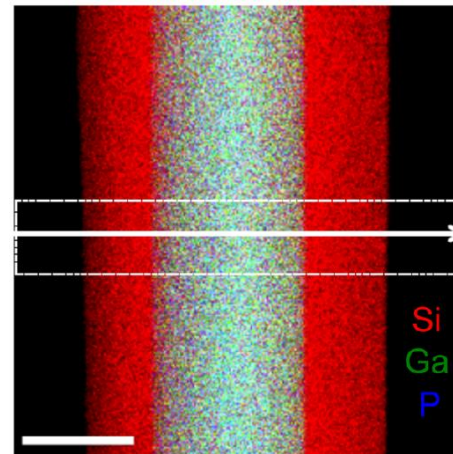
Experimental Realization of Hex-Si/Ge

Crystal transfer



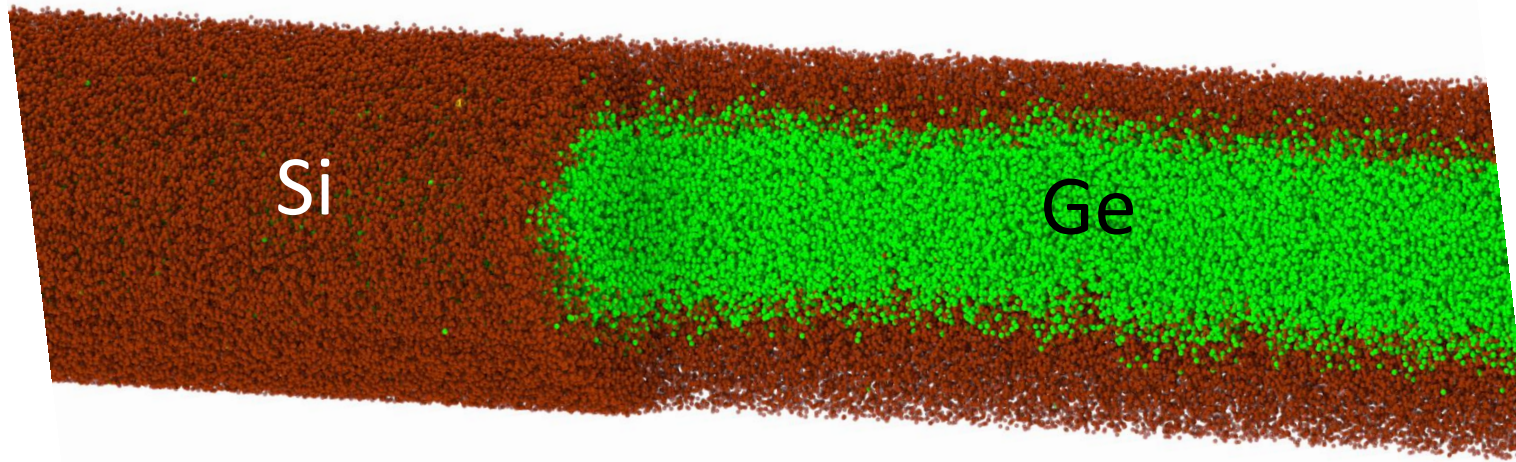
R.Algra et al., *Nano Lett.*, **2011**, *11*, 1690–1694
Hauge et al., *Nano Lett.* **2015**, *15*, 5855–5860
Hauge et al., *Nano Lett.* **2017**, *17*, 85–90

EDX Compositional Maps



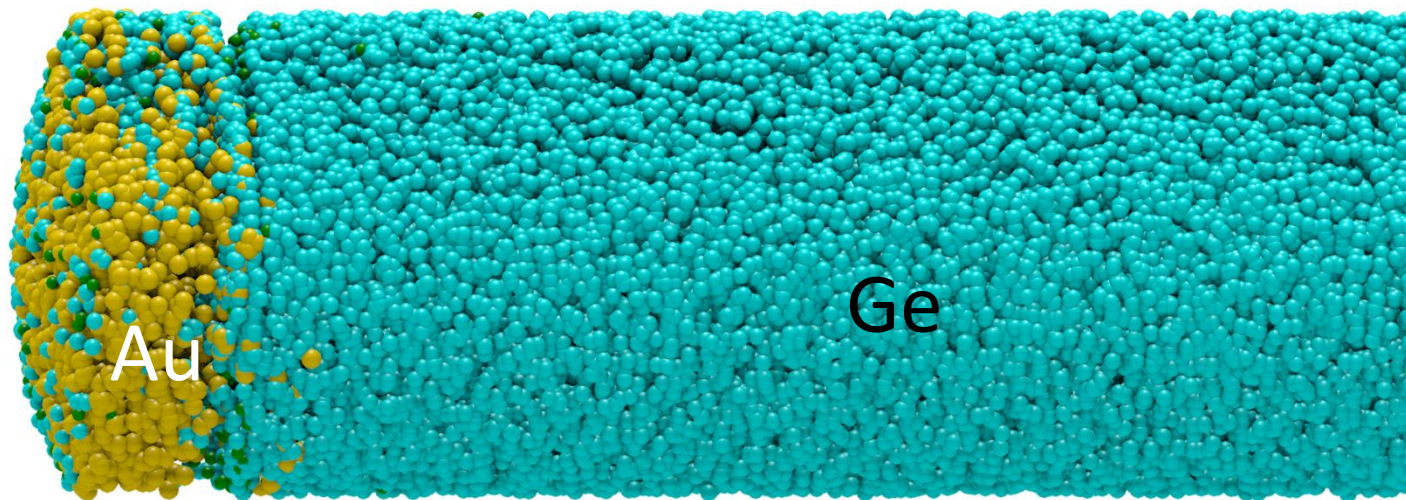
Atom by Atom Characterization

Atom Probe Tomography Technique

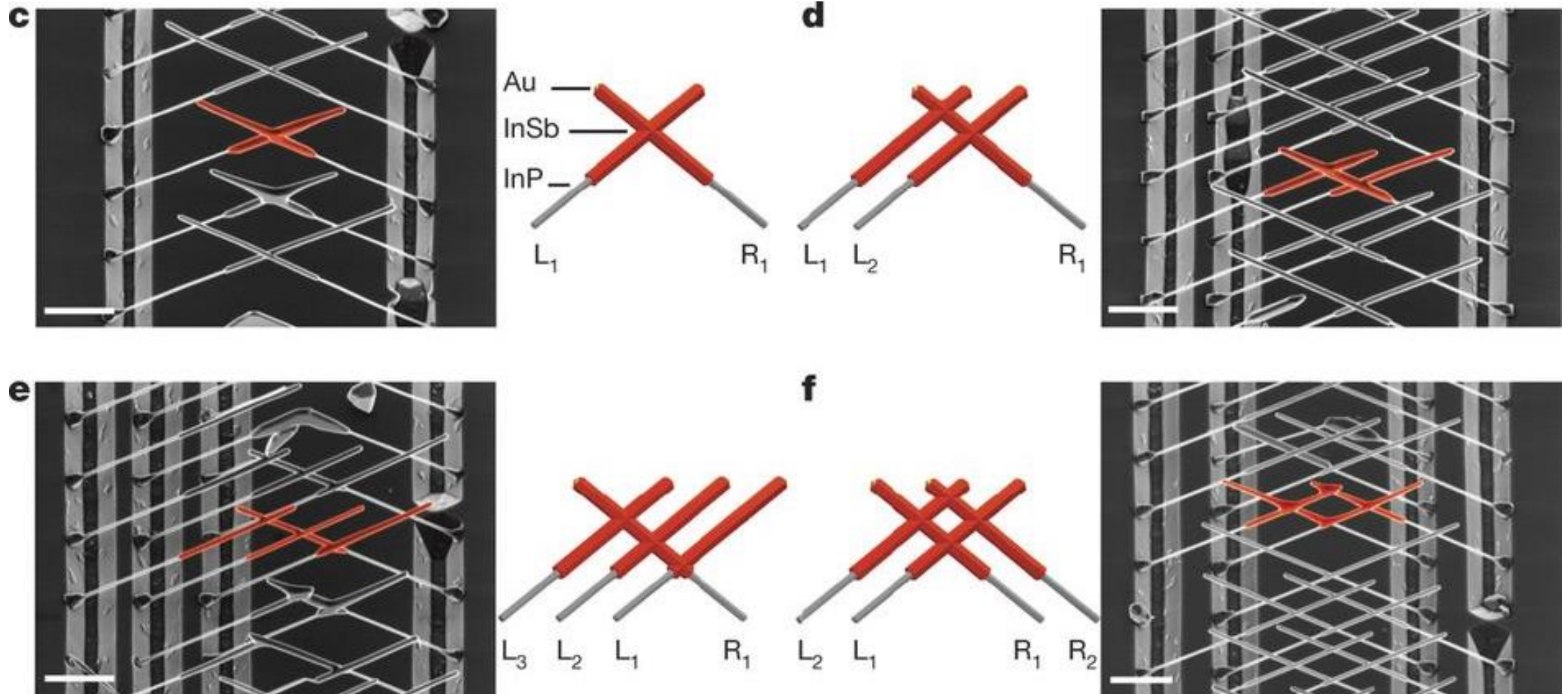


- Identify the chemical composition down to atomic precision.

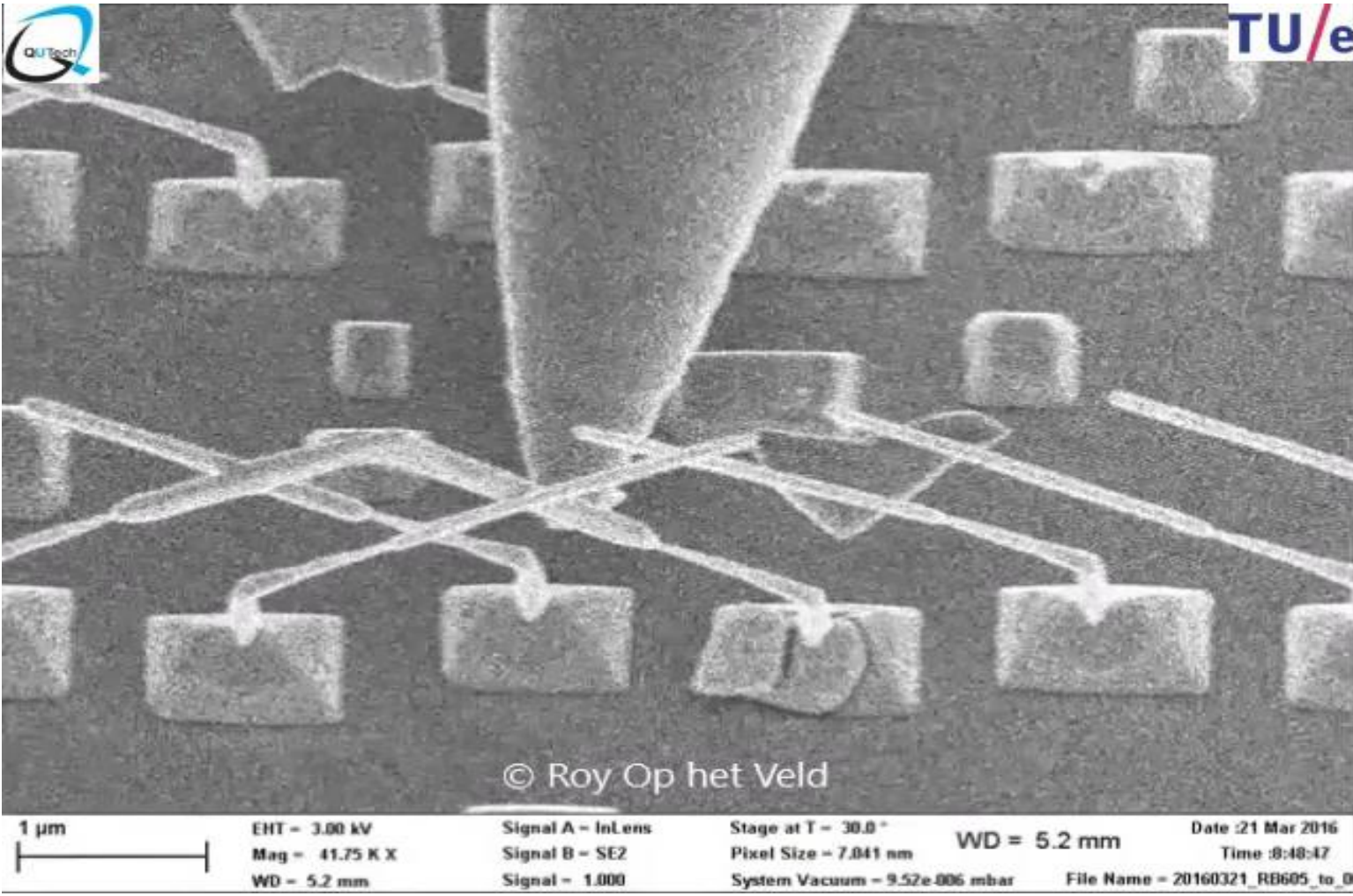
- Identify doping levels



Example 1: Electrical Characterization of InSb NWs for Quantum Applications

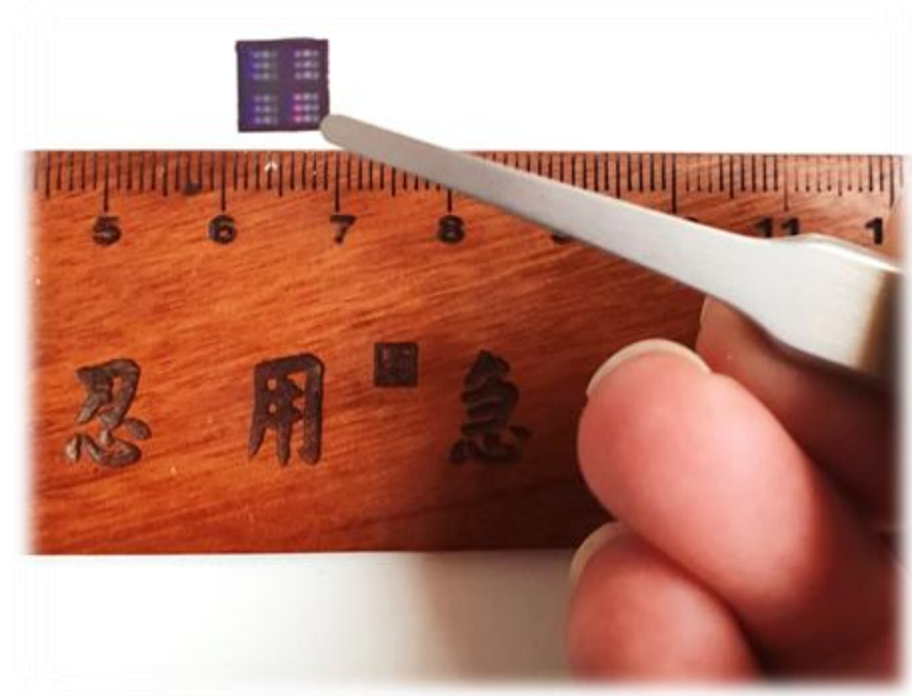
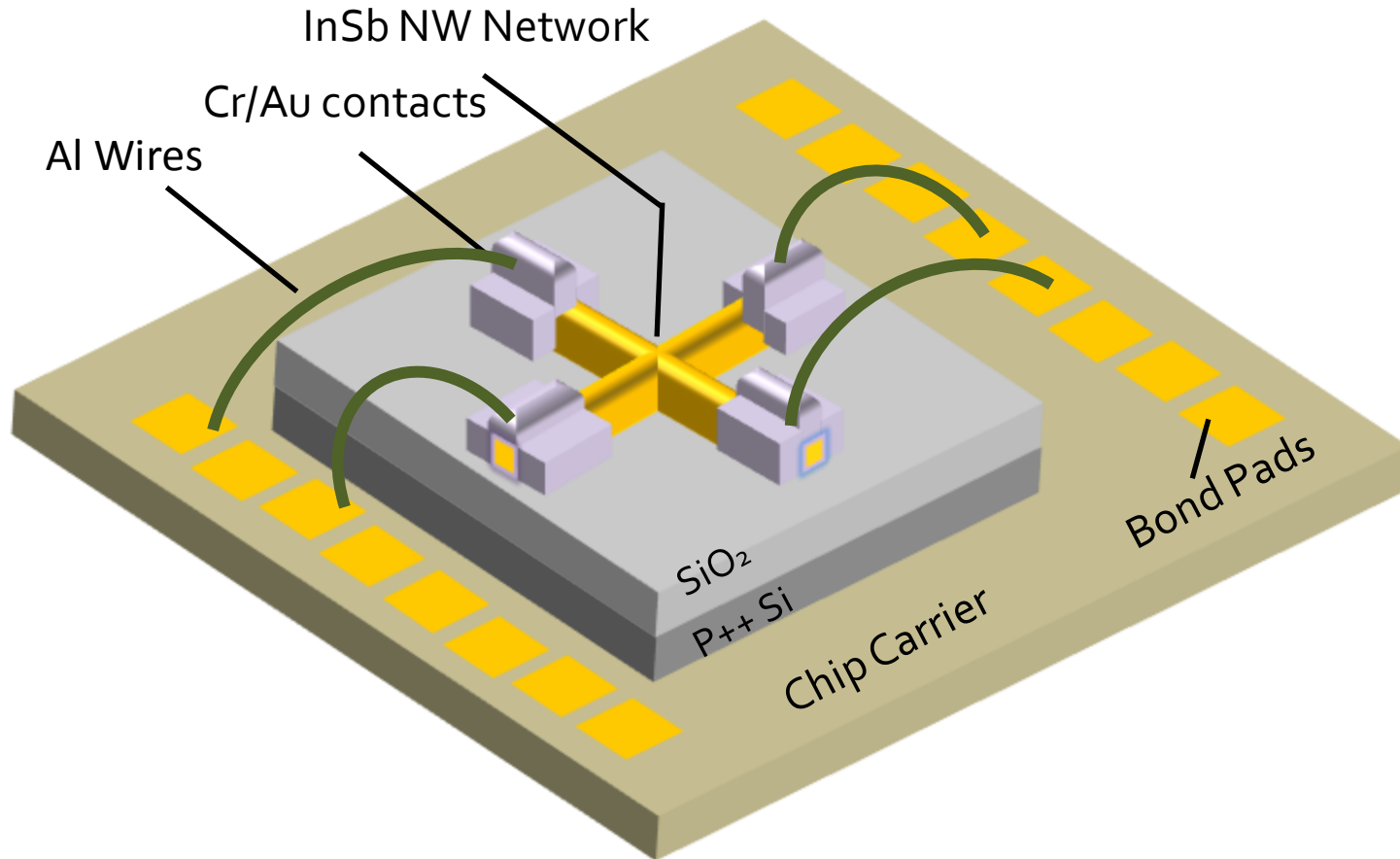


Deterministic Transfer of NW networks



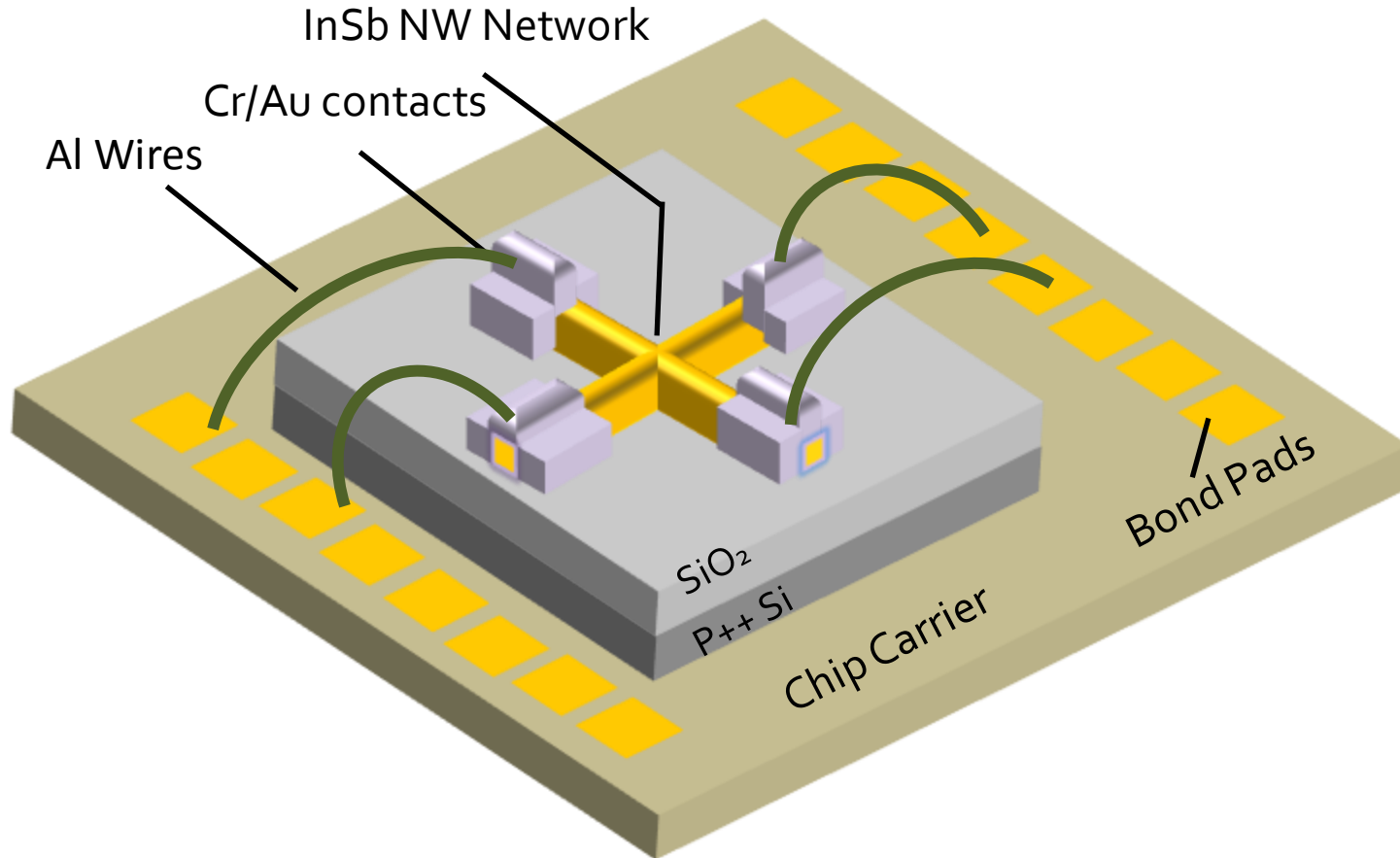
Scanning Electron Microscope

Device Fabrication

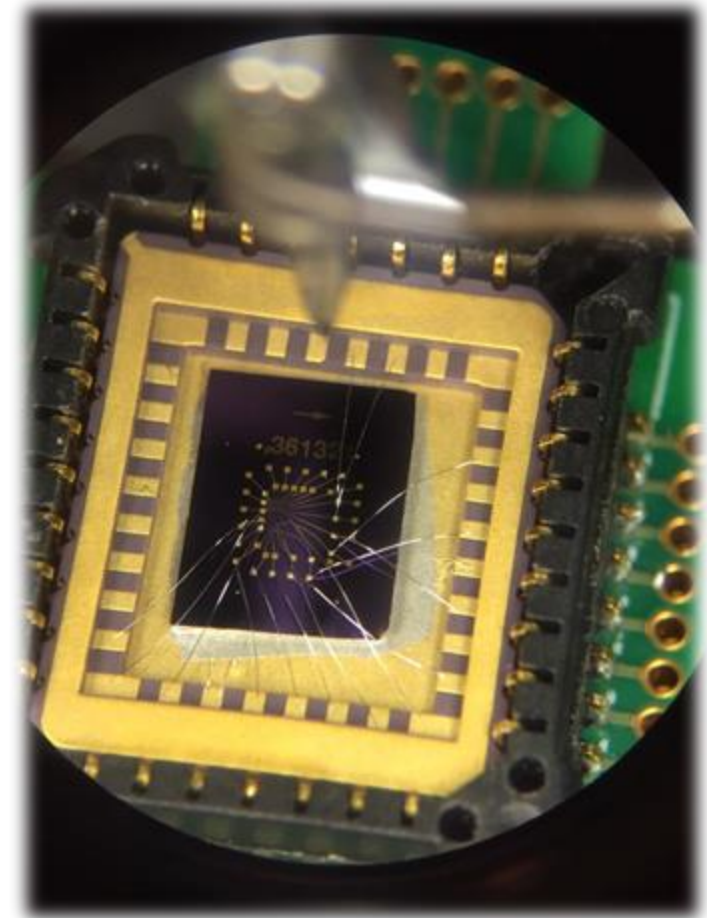


Device chip wire bonded to a chip carrier

Device Fabrication

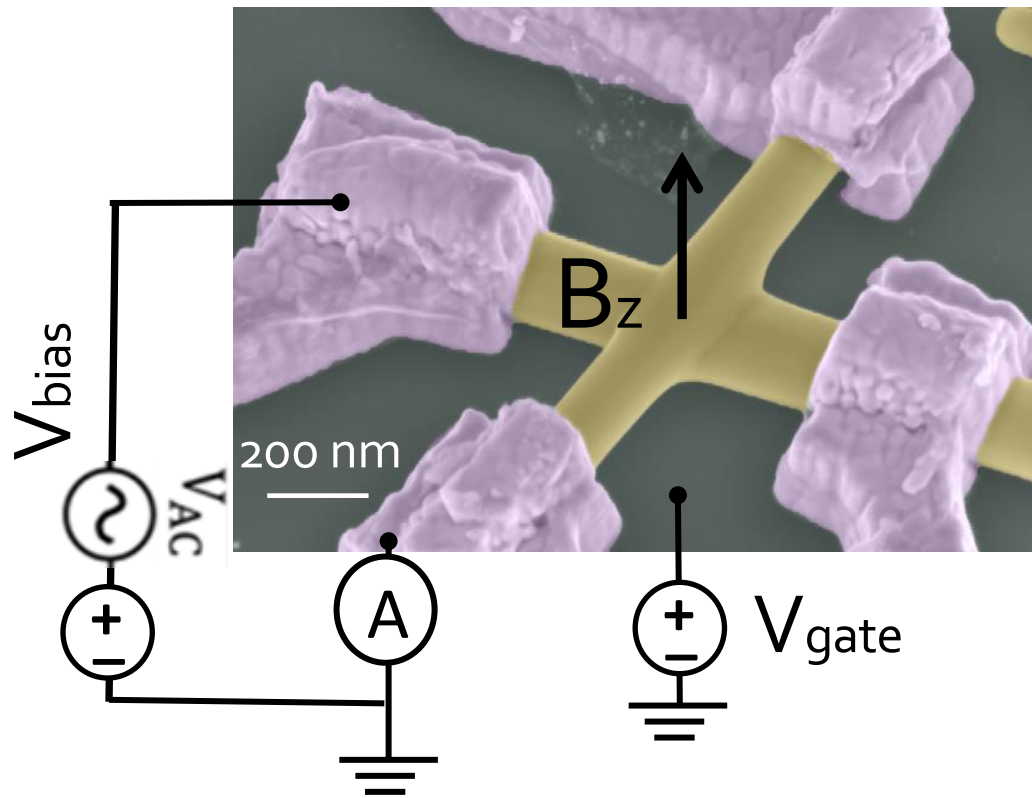


Device chip wire bonded to a chip carrier



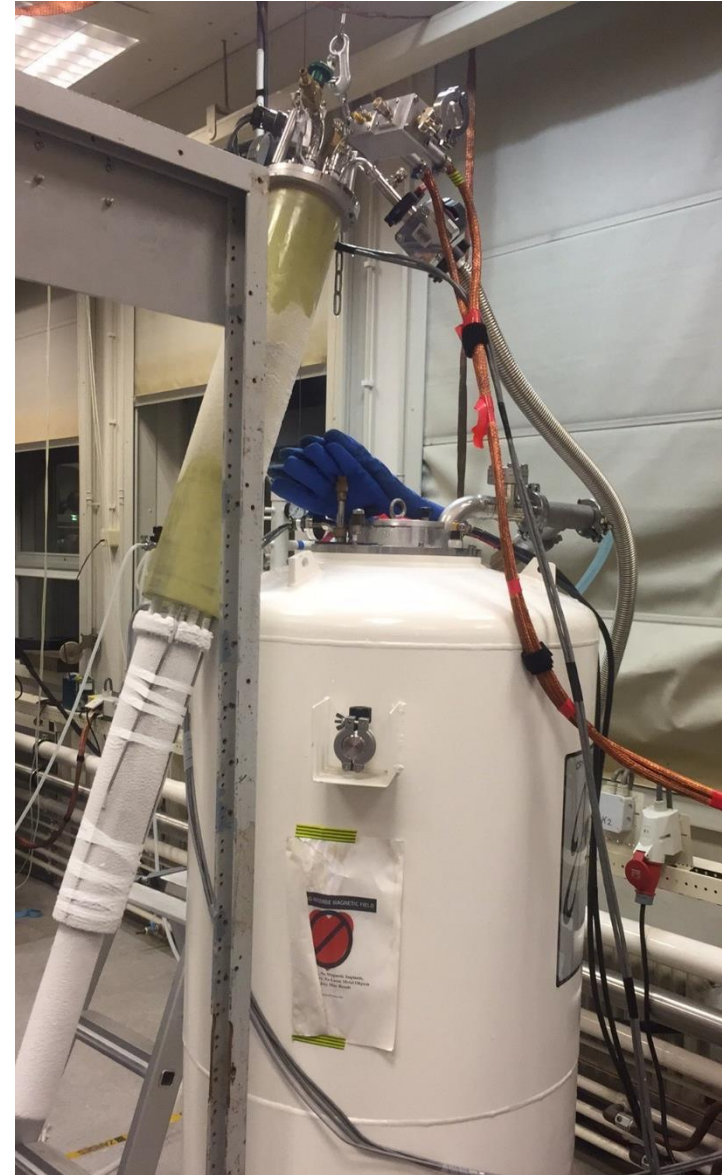
Chip Carrier mounted on PCB

Electronic Transport Measurement Setup

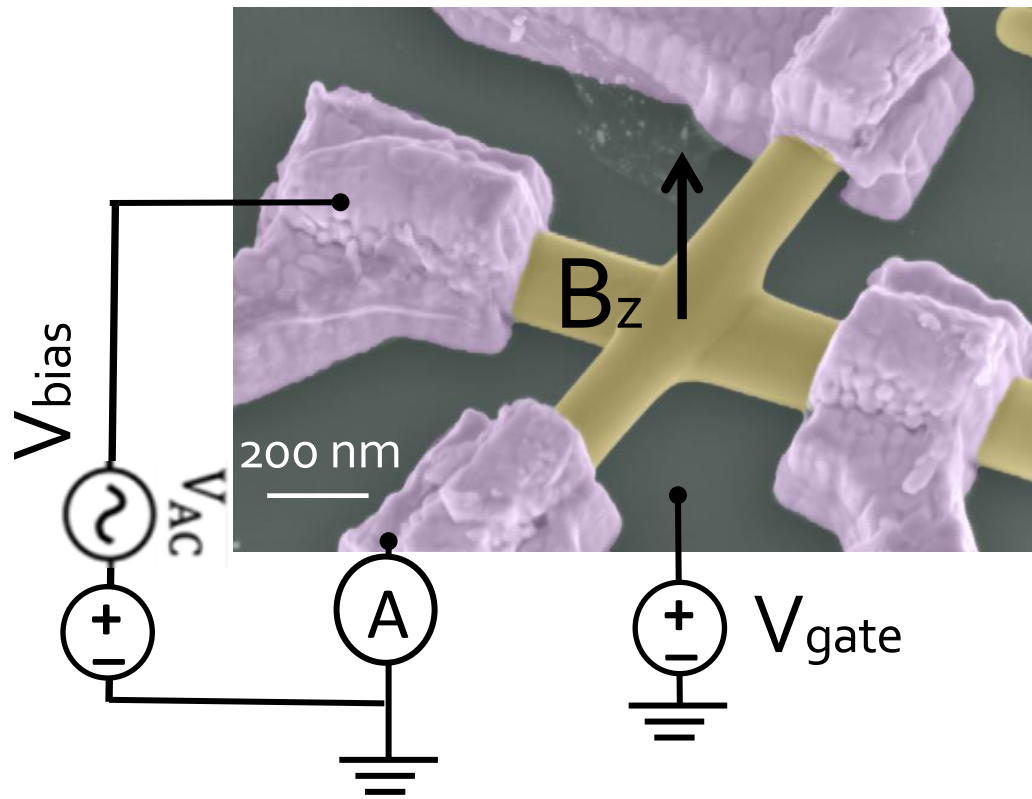


Temperature = 300 mK = -273 C

E.M. T. Fadaly et al., Nano Lett., 2017, 17(11), pp 6511–6515

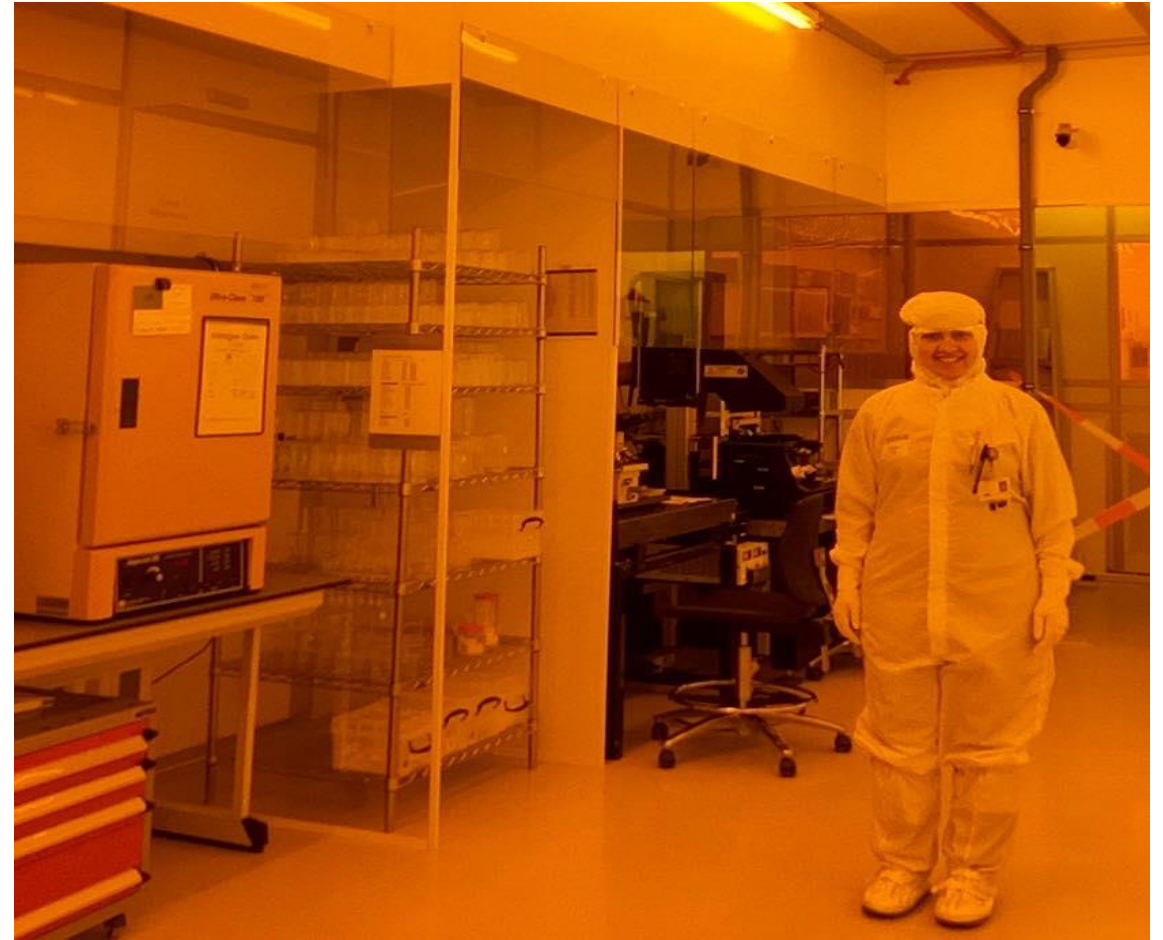


Electronic Transport Measurement Setup



Temperature = 300 mK = -273 C

E.M. T. Fadaly et al., Nano Lett., 2017, 17(11), pp 6511–6515



Device Fabrication in Cleanroom

Summary

❑ Condensed Matter Physics:

- ✓ Examples of inorganic semiconducting materials
- ✓ Physics of Semiconducting Materials
- ✓ Dimensionality and Size effects on the electronic and optoelectronic properties

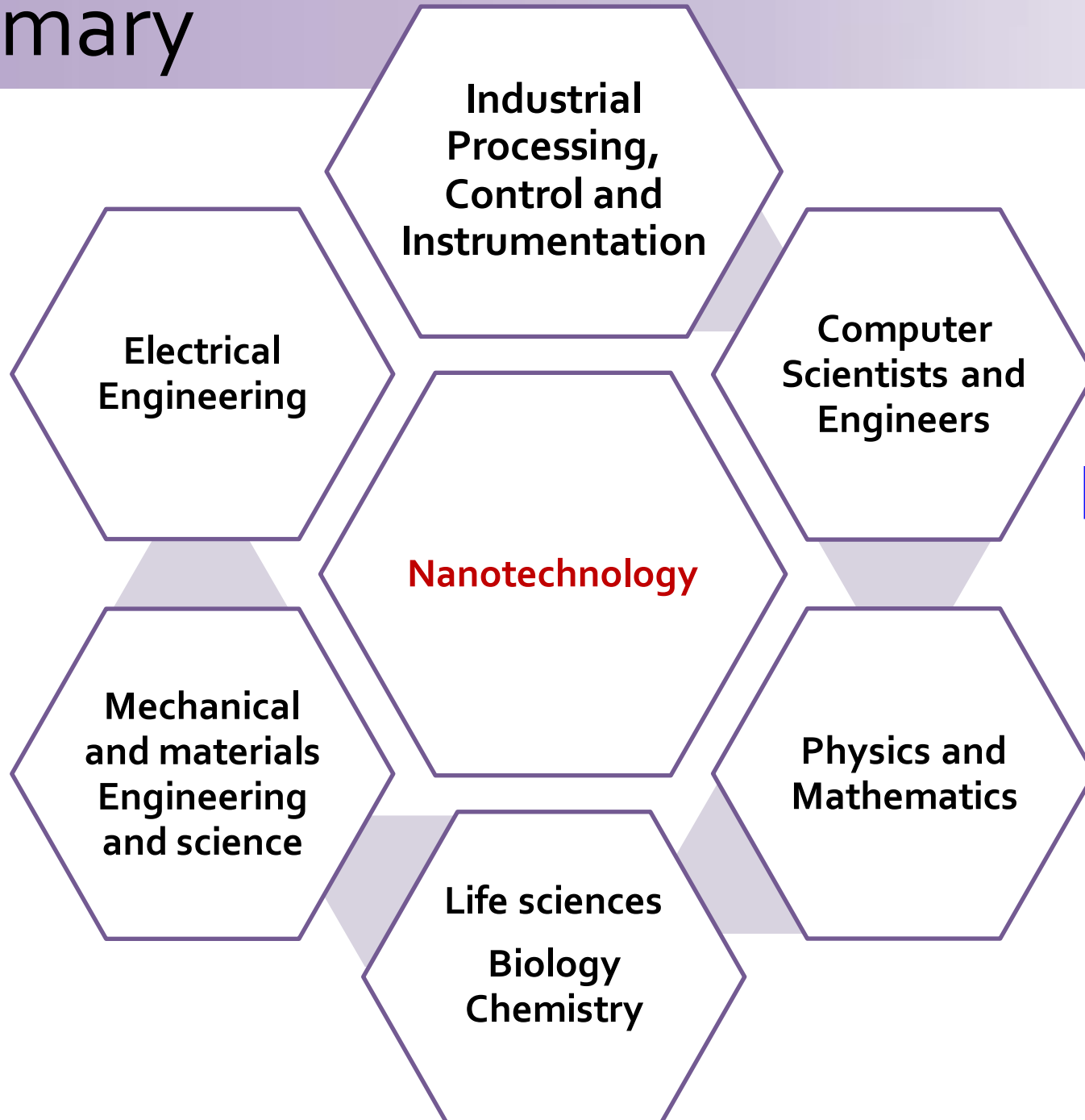
❑ Motivation of working on novel nanomaterials

- ✓ Miniaturization of devices and new functionalities
- ✓ ITRS and technology nodes for scaling down
- ✓ The quest for new design concepts and novel materials with unique properties

❑ Examples of real research on 1D- nanomaterials : Nanowires

- ✓ Electrical characterization of multiterminal NWs for Quantum computing applications
- ✓ Modification of atomic ordering of certain materials for light applications
- ✓ Different characterization techniques: Structural (TEM, SEM, EDX), Electrical (low T transport measurements)

Summary



Boundaries between sciences start to disappear!