Low Dimensional Systems and Nanostructures

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1. Length scales and low dimensional systems
2. Electronic states in confined systems and low dimensions
3. Response properties of the electron system in reduced dimensions

1. Length scales and low dimensional systems

Outline

1.1 Nano, meso, and macro scales

1.2 Dimensionality

- Chemical bonding approach
- Physical length scales approach
  - De Broglie length, Fermi wave-length
  - Mean free path

1.3 Transport regimes

1.4 Examples of low-dimensional systems

- 2D: transition metal dichalcogenides, semiconducting chalcogenides, layered halogen compounds, graphene, FeSe
- 1D: polymers, inorganic chains, nanotubes, metallic wires, nanowires on surface
- 0D: fullerenes, quantum dots, atomic clusters, synthetic nanocrystals

1. Length scales and low dimensional systems

Outline

1.5 Fabrication and characterization techniques

- Nanolitography
- Atomic Force Microscopy (AFM)
- Scanning Tunneling Microscope (STM)
- Molecular Beam Epitaxy (MBE)

1.6 Exercise

1. Length scales and low dimensional systems

1.1 Nano, meso, and macro scales

Macro scale

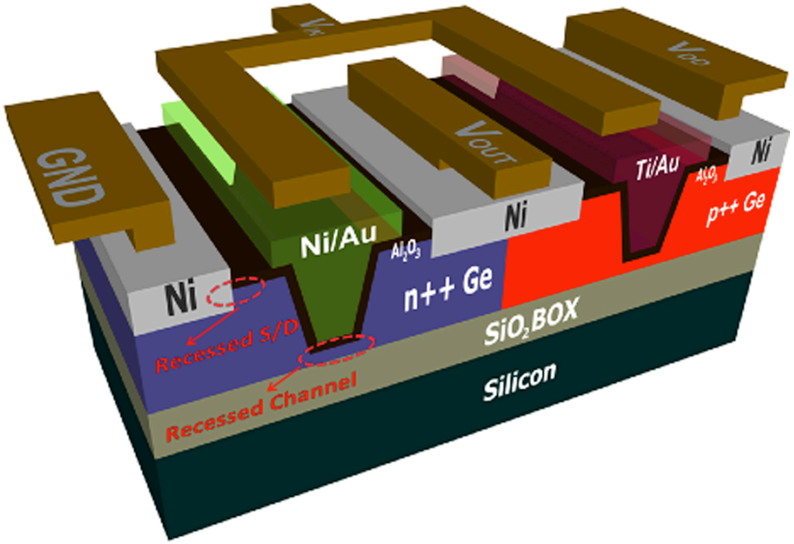
- The scale of our everyday life
- The properties of materials are defined by physical bulk properties:
  - Color
  - Density
  - Stiffness
  - Sound velocity
  - Bending rigidity
  - …
- Classical mechanics are enough

1. Length scales and low dimensional systems

1.1 Nano, meso, and macro scales

Meso scale

- The scale in between the bulk and the atomic limits
- Mesoscopic physics study the properties of small condensed objects
- Bulk properties of materials may be used and classical mechanics may be used
- Quantum mechanical effects appear and may be important

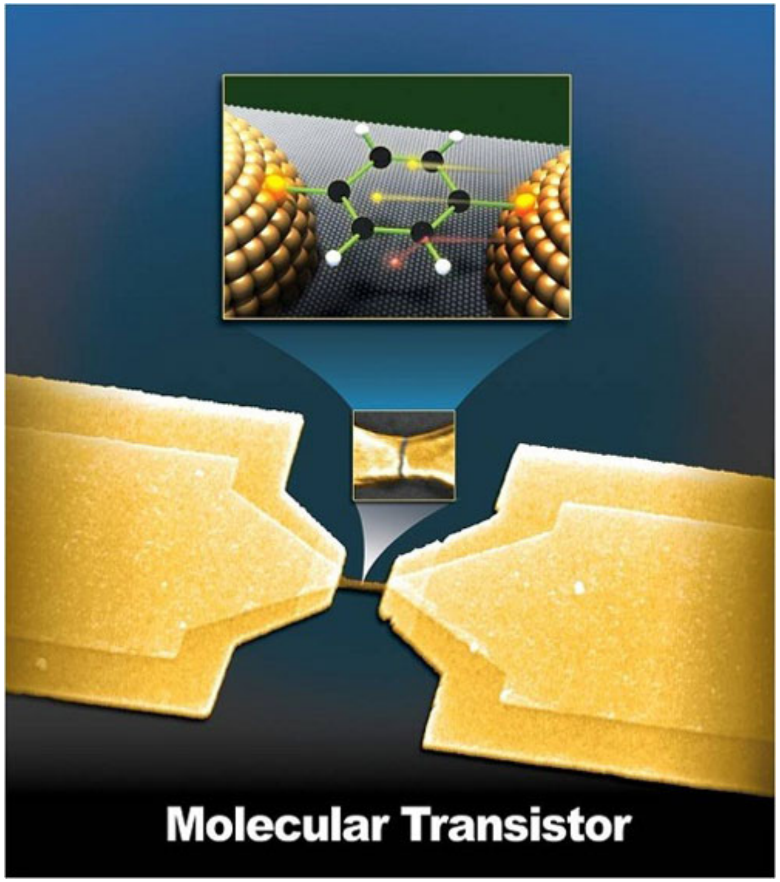


1. Length scales and low dimensional systems

1.1 Nano, meso, and macro scales

Nano scale

- The scale of the atomic limit
- Bulk properties make no sense
- The quantum nature of the electrons is crucial
- Quantum mechanical description

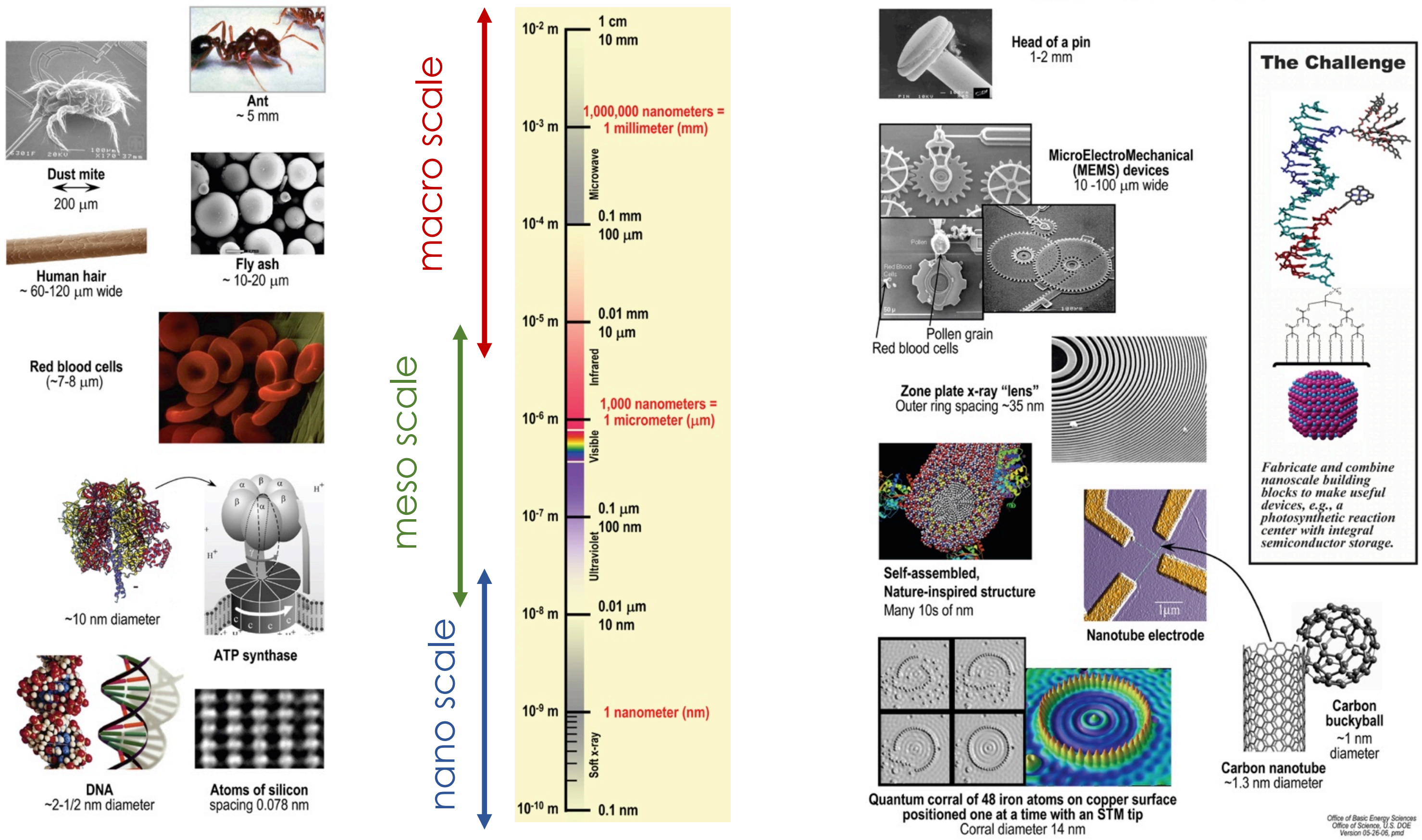


1. Length scales and low dimensional systems

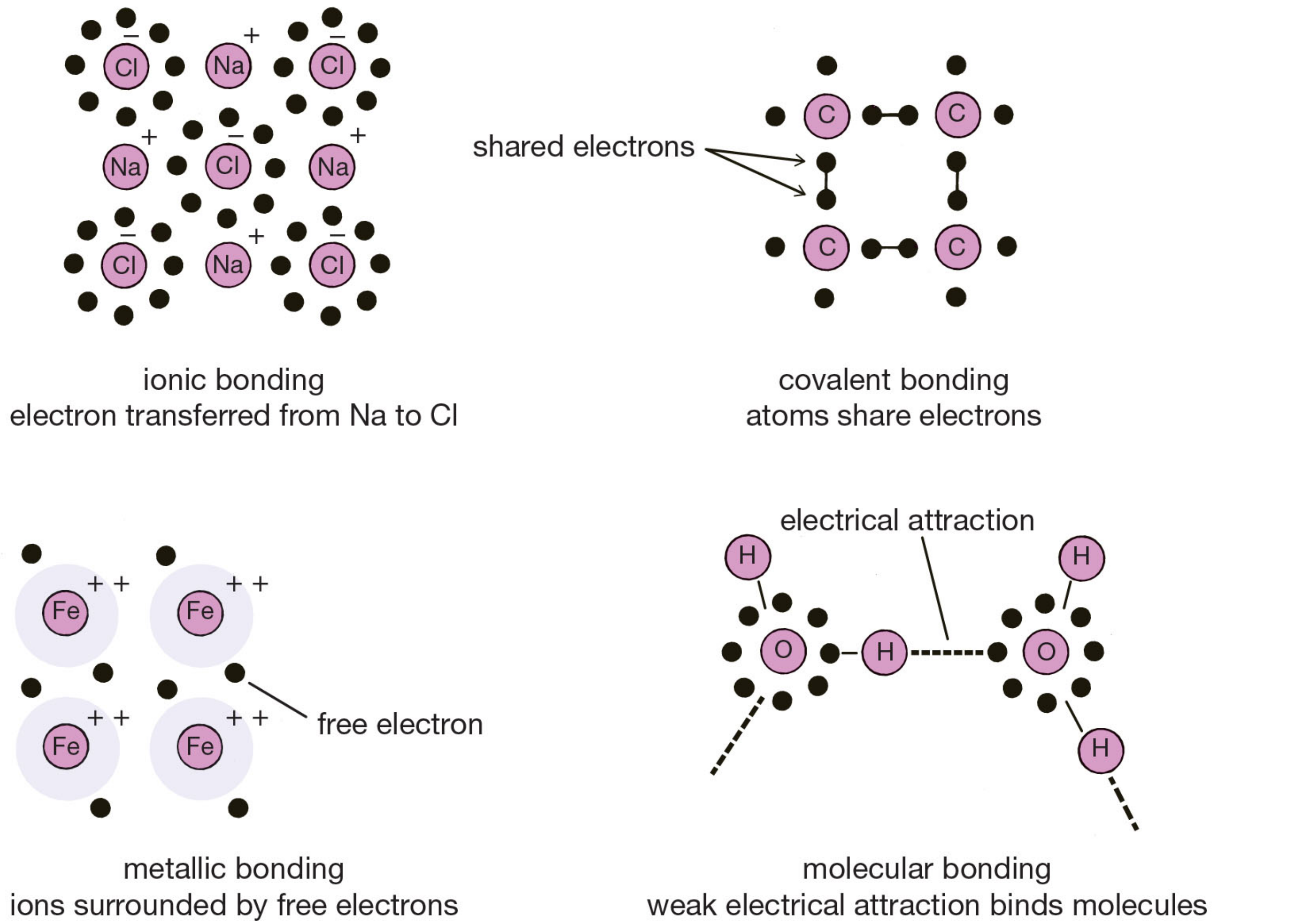
1.1 Nano, meso, and macro scales

Natural things

Man-made things



Chemical bonding approach

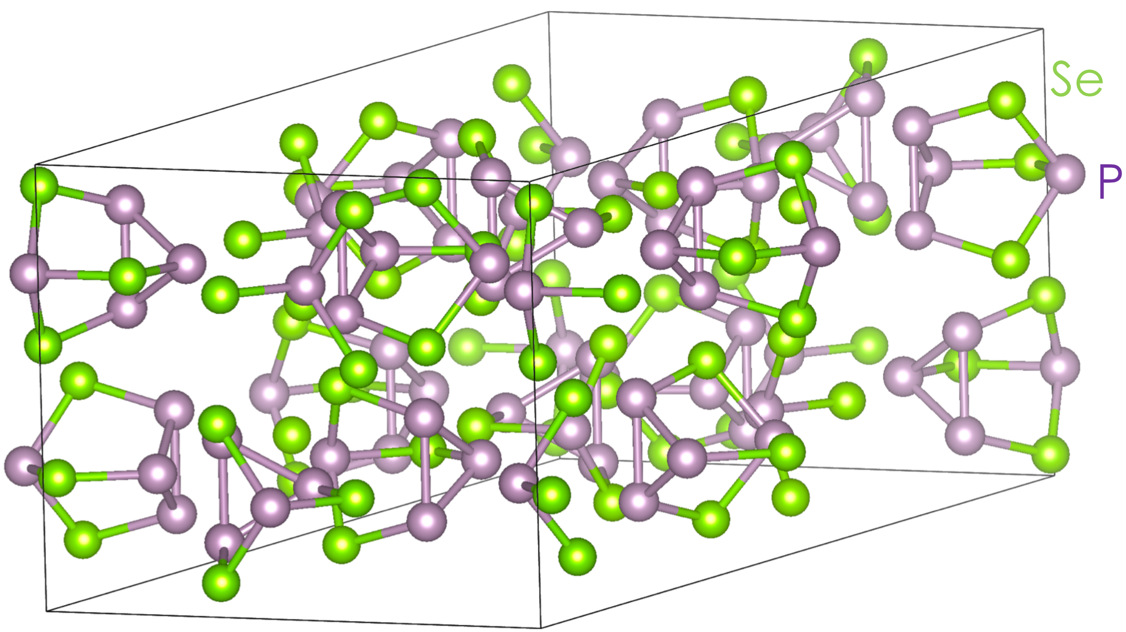


Chemical bonding approach

- In a given compound there might be units strongly bonded by covalent bonds
- These units interact among themselves by weak forces, e.g. hydrogen bonds, Van der Waals forces.
- Depending on the dimension of the unit: 0D, 1D, 2D, 3D systems

Chemical bonding approach: 0D

P_4Se_3

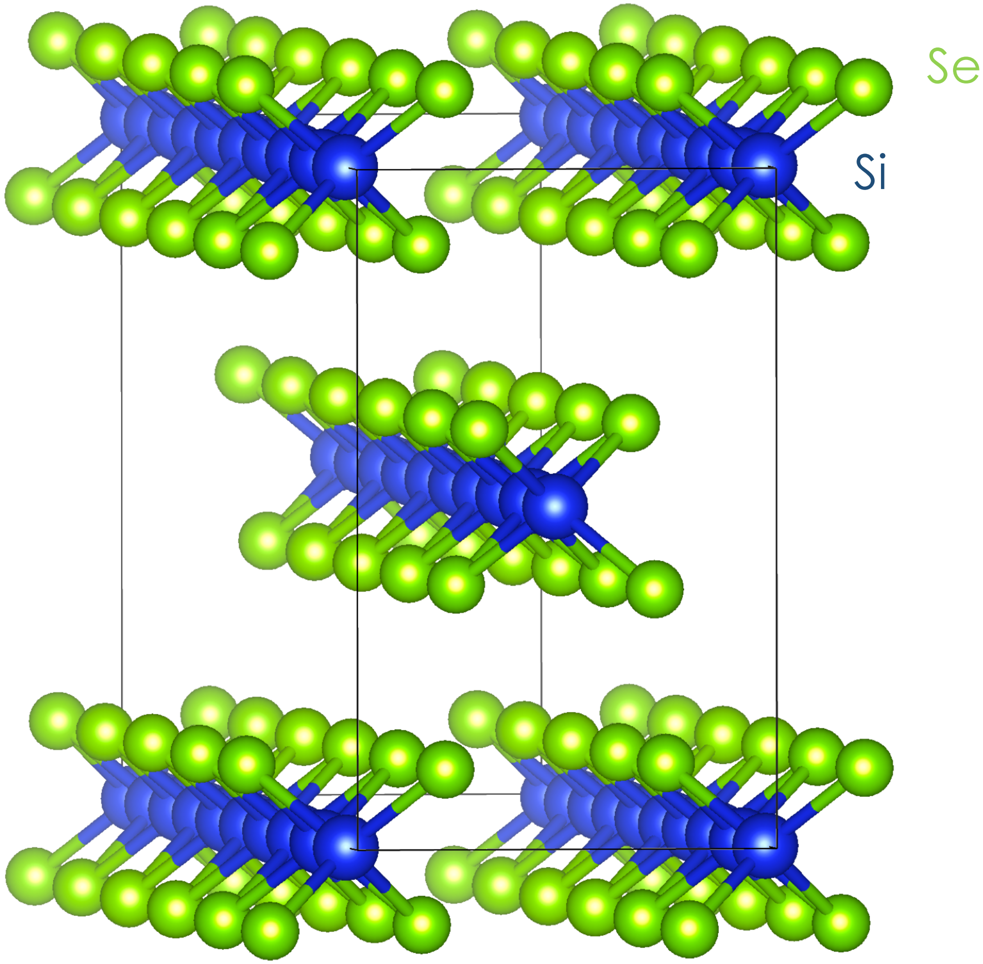


1. Length scales and low dimensional systems

1.2 Dimensionality

Chemical bonding approach: 1D

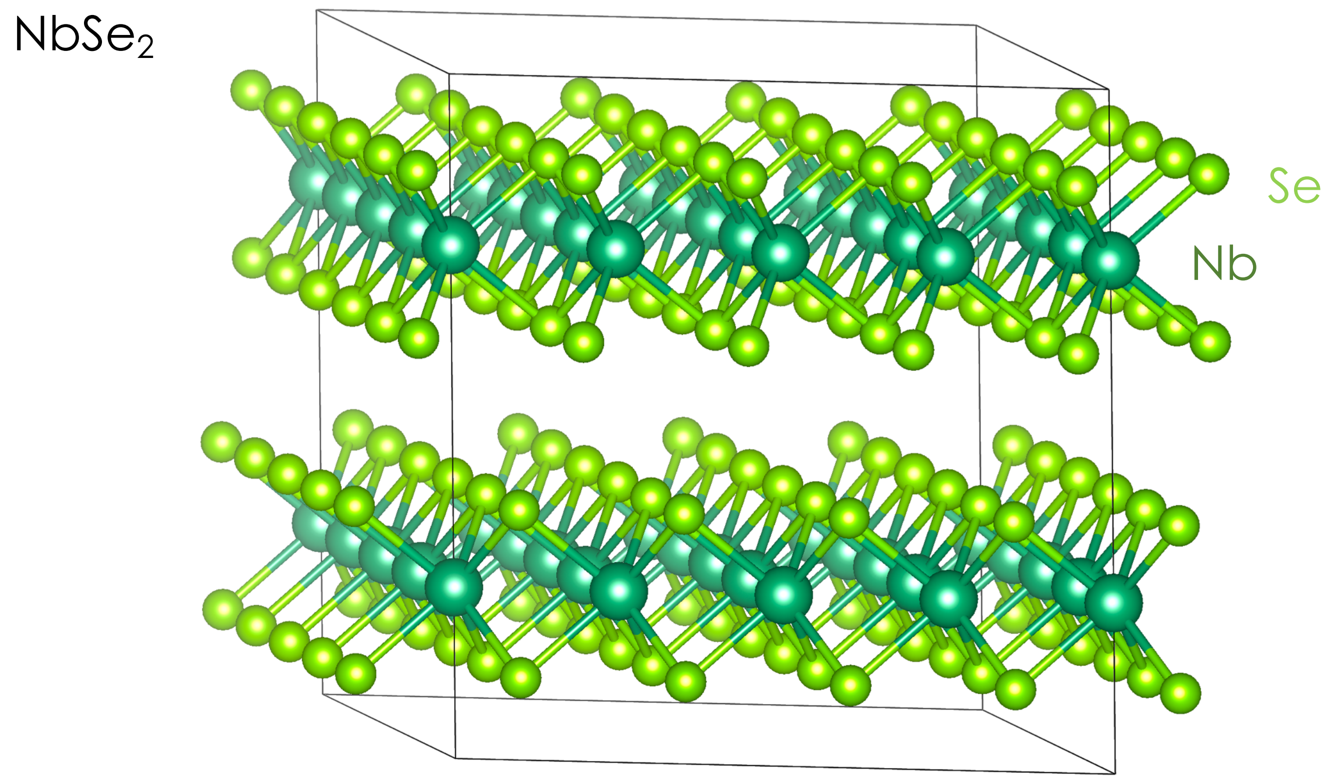
$SiSe_2$



1. Length scales and low dimensional systems

1.2 Dimensionality

Chemical bonding approach: 2D

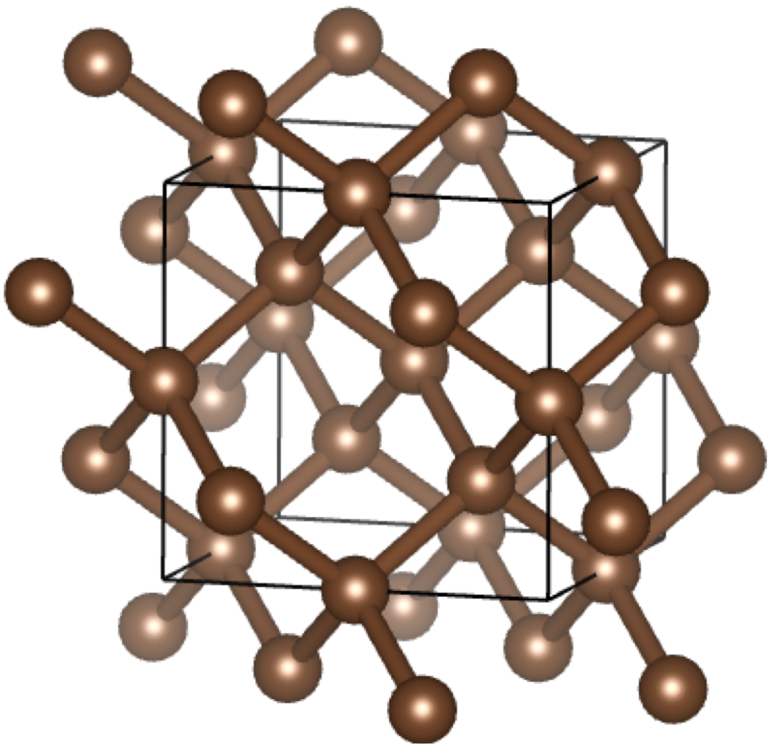


1. Length scales and low dimensional systems

1.2 Dimensionality

Chemical bonding approach: 3D

Diamond



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1. Length scales and low dimensional systems

1.2 Dimensionality

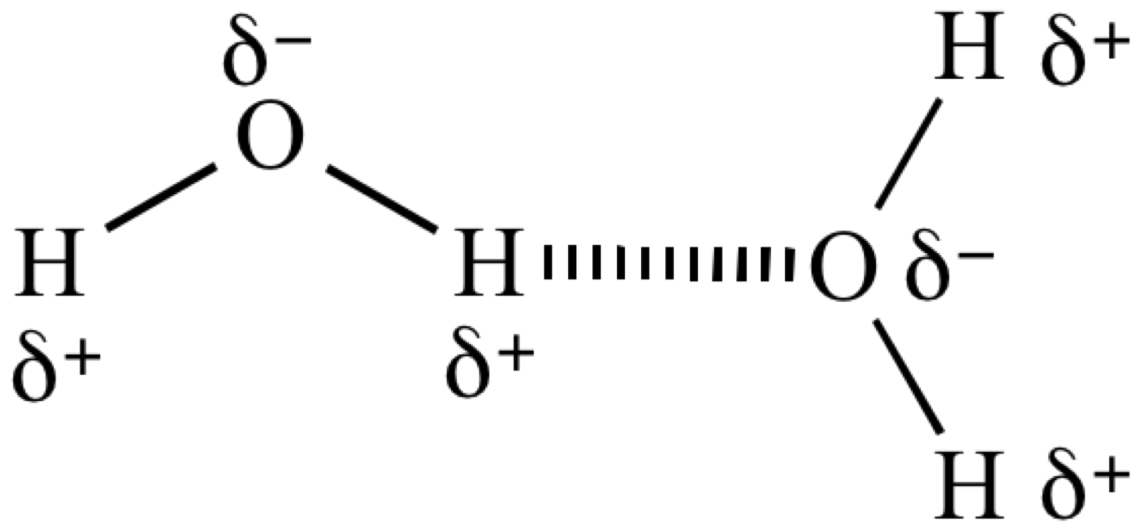
Van der Waals forces

- Intermolecular forces, or forces between strongly bonded covalent units
  - **Debye forces:** Dipole-dipole interactions
  - **Hydrogen bonds:** Dipole-dipole interactions with hydrogen
  - **London dispersion forces:** Instantaneous dipole-induced dipole interactions in non-polar materials
  - Dipole-induced dipole interactions

Van der Waals forces

- **Debye forces (hydrogen bonds):**
  Dipole-dipole interactions

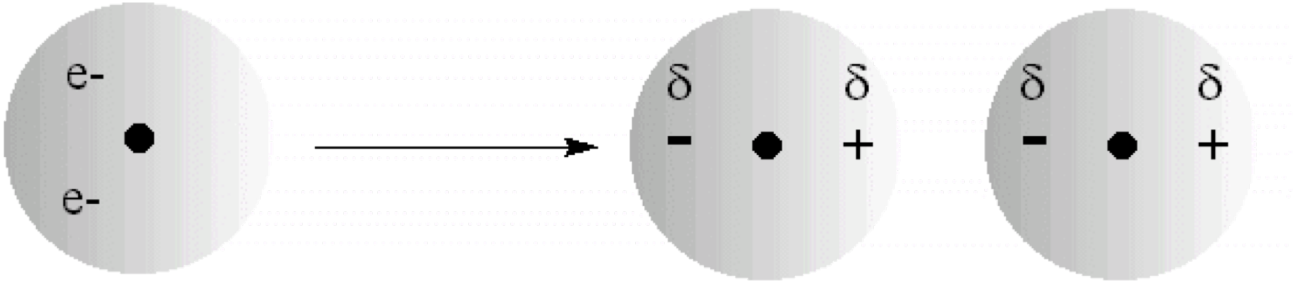
$F \sim r^{-3}$



Van der Waals forces

- **London dispersion forces:** Instantaneous dipole-induced dipole interactions in non-polar materials

$F \sim r^{-6}$



Instantaneous uneven distribution of electrons in He atom

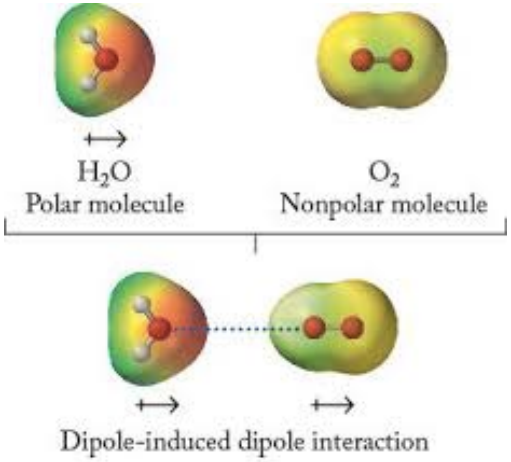
Instantaneous dipole

Induced dipole on neighboring He atom. Resultant attractive force

Van der Waals forces

- Dipole-induced dipole interactions

$F \sim r^{-6}$

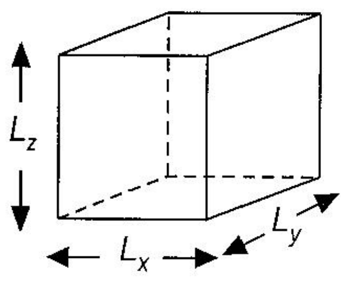


1. Length scales and low dimensional systems

1.2 Dimensionality

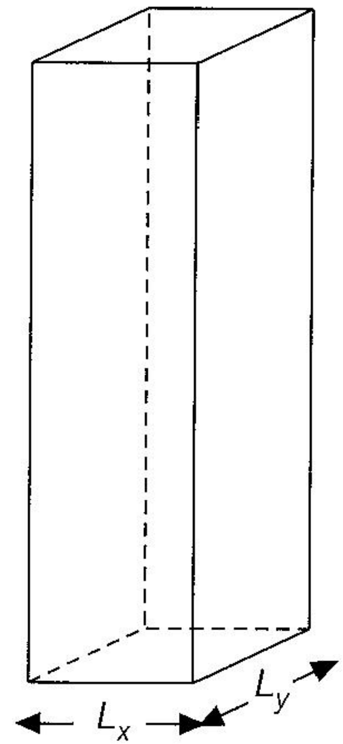
Physical length scales approach

- Based on size dependence of a physical property, e.g. electronic or phonon transport
- Reduced dimension if the dimension of the sample is smaller than a characteristic length L_0



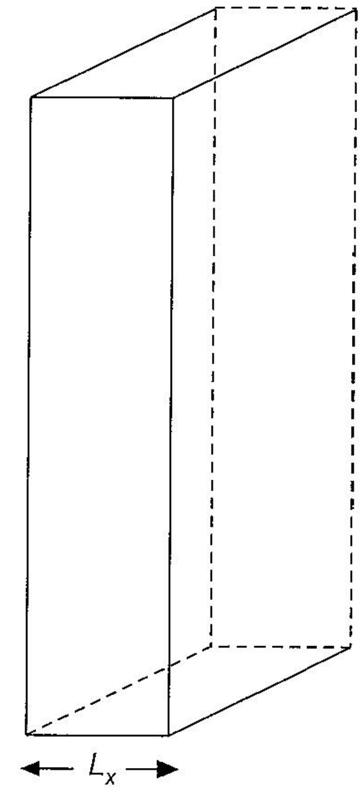
$$L_x, L_y, L_z < L_0$$

0D: Quantum dot



$$L_x, L_y < L_0$$

1D: Quantum wire



$$L_x < L_0$$

2D: Quantum well

Physical length scales approach:

- **De Broglie wavelength**:
The (wave)length at which a particle with momentum *p* shows wave-like (quantum mechanical) behavior

$$\lambda = h/p$$

$$\omega = ck$$

- **Fermi wavelength**:
The (wave)length at which an electron in a metal with energy E_F (Fermi energy) shows wave-like (quantum mechanical) behavior

$$\lambda_F = \sqrt{\frac{h^2}{2mE_F}}$$

$$v_F = \frac{h}{\lambda_F m}$$

1. Length scales and low dimensional systems

1.2 Dimensionality

Physical length scales approach:

Element	E_F (eV)	v_F (10^6 m/s)	λ_F (Å)
Li	4.74	1.29	5.65
Be	7.08	1.28	5.69
K	2.12	0.86	8.47
Pb	9.47	1.83	3.98

1. Length scales and low dimensional systems

1.2 Dimensionality

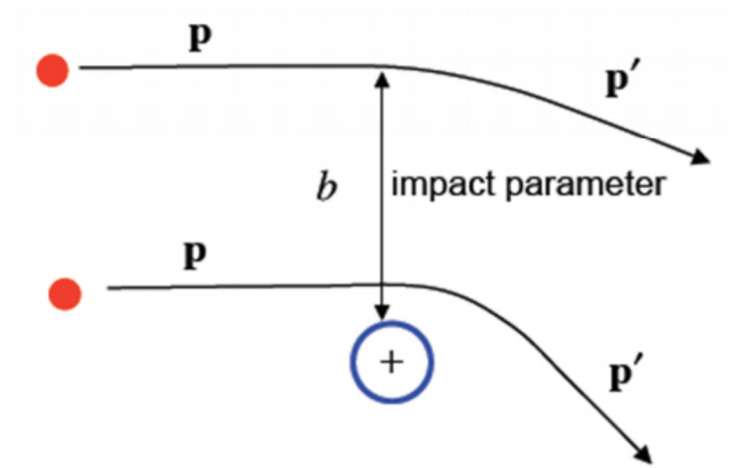
Physical length scales approach:

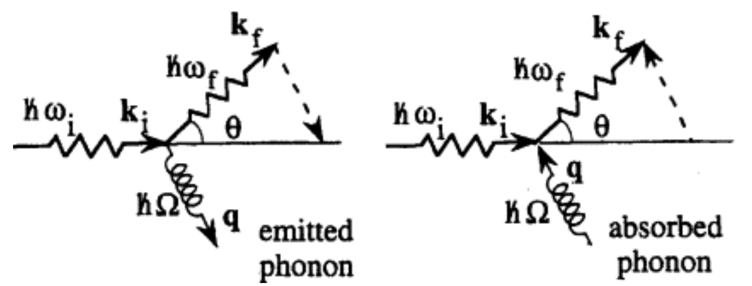
- **Mean free path**: L_m

  The average distance an electron travels before it experiences a scattering process that changes its initial momentum
  - **Elastic scattering**:
    - When the energy of the electron is conserved
    - Impurity scattering mainly
  - **Inelastic scattering**:
    - When the energy of the electron is not conserved
    - Electron-electron and electron-phonon scattering mainly

  It is related to the relaxation time τ, for a material with carrier velocity v.

$$L_m = v\tau$$

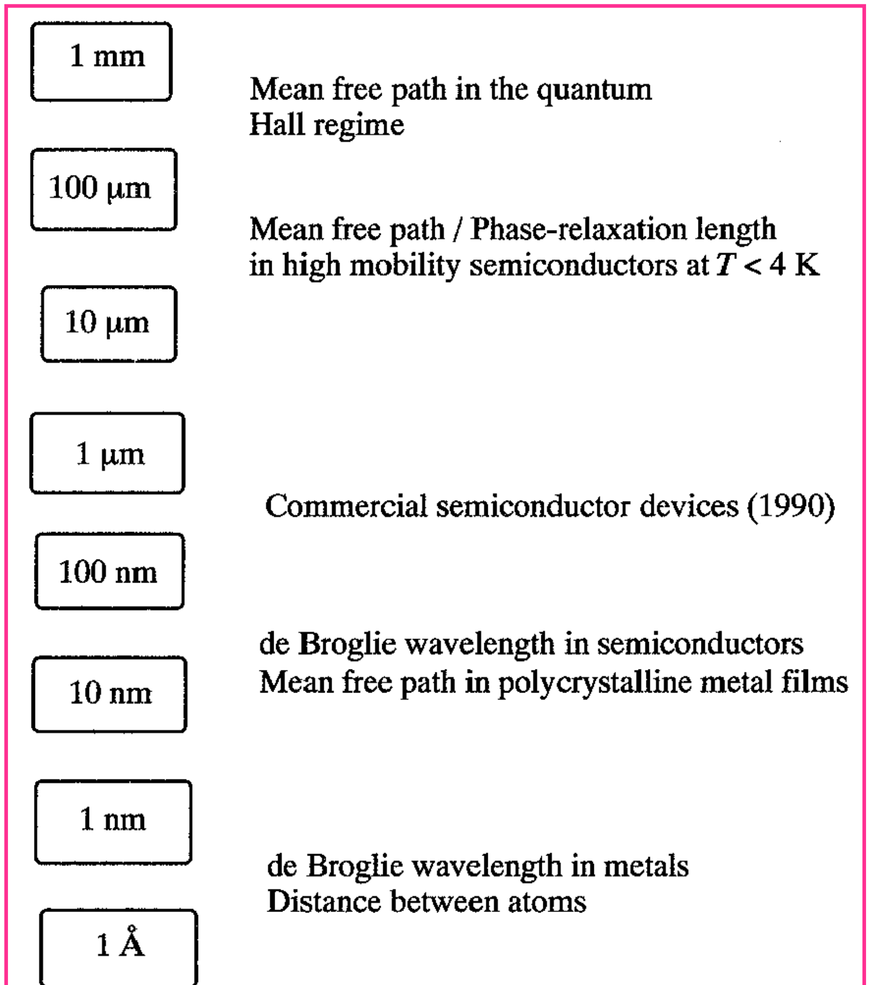




1. Length scales and low dimensional systems

1.2 Dimensionality

Physical length scales approach:

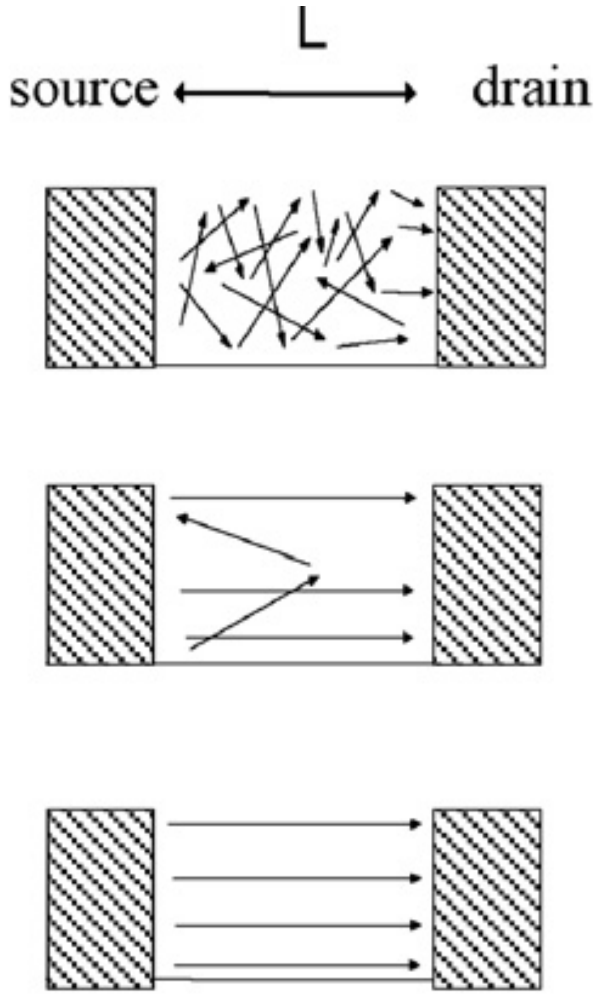


S. Datta, "Electronic transport in mesoscopic systems" (1995)

1. Length scales and low dimensional systems

1.3 Transport regimes

Transport through a constriction:

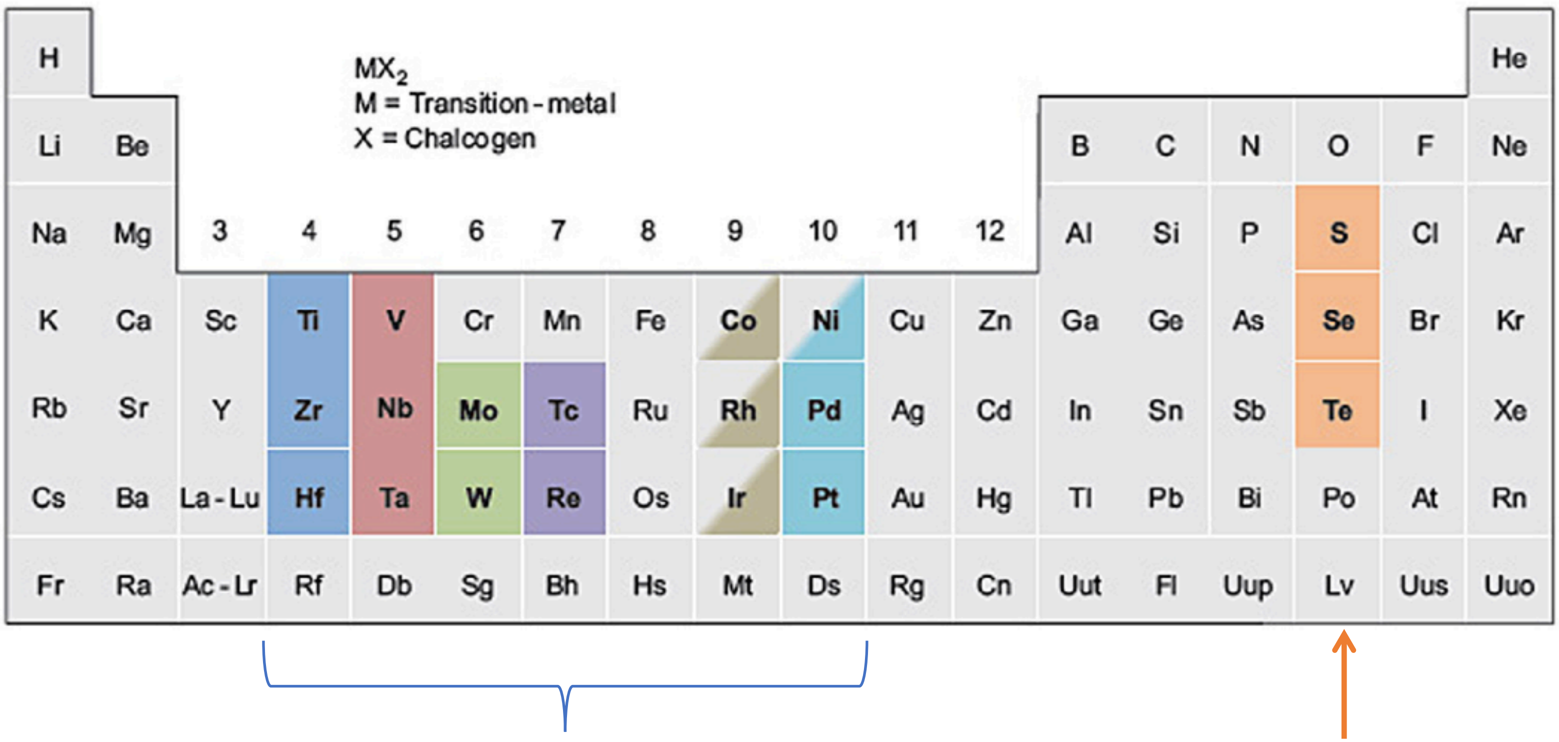


Diffusive $L_m \ll L$

Quasi-ballistic $L_m \sim L$

Ballistic $L_m \gg L$

2D: Transition metal dichalcogenides (TMDs)

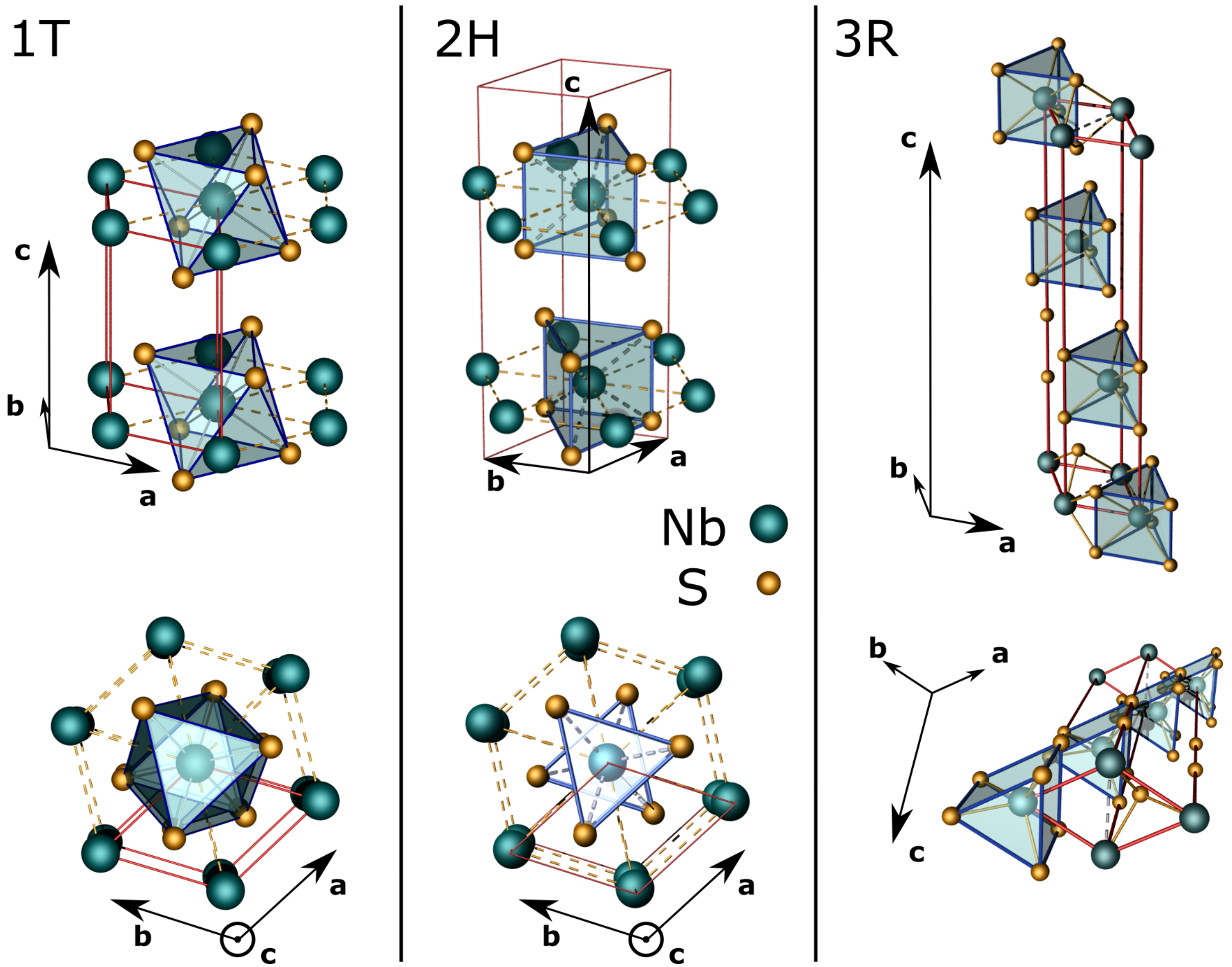


Transition metal

Chalcogen

2D: Transition metal dichalcogenides (TMDs)

Crystal structures

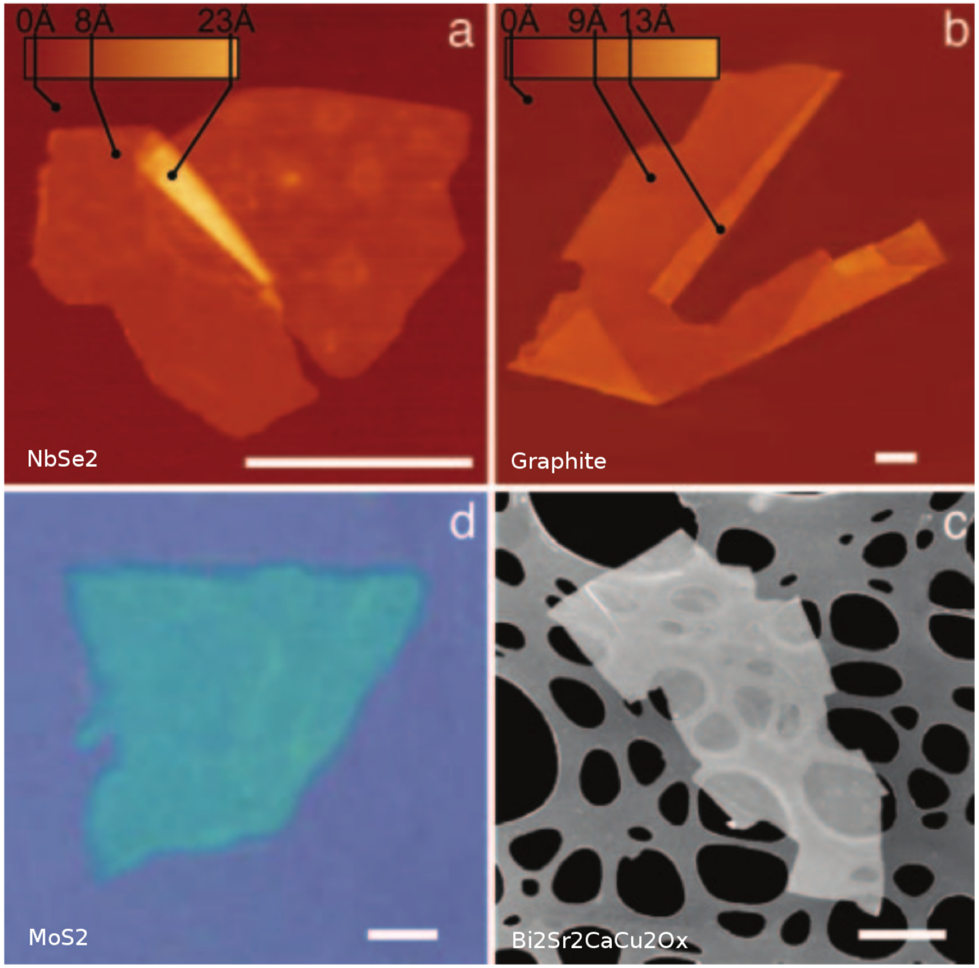


1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

2D: Transition metal dichalcogenides (TMDs)

Exist in the 2D limit



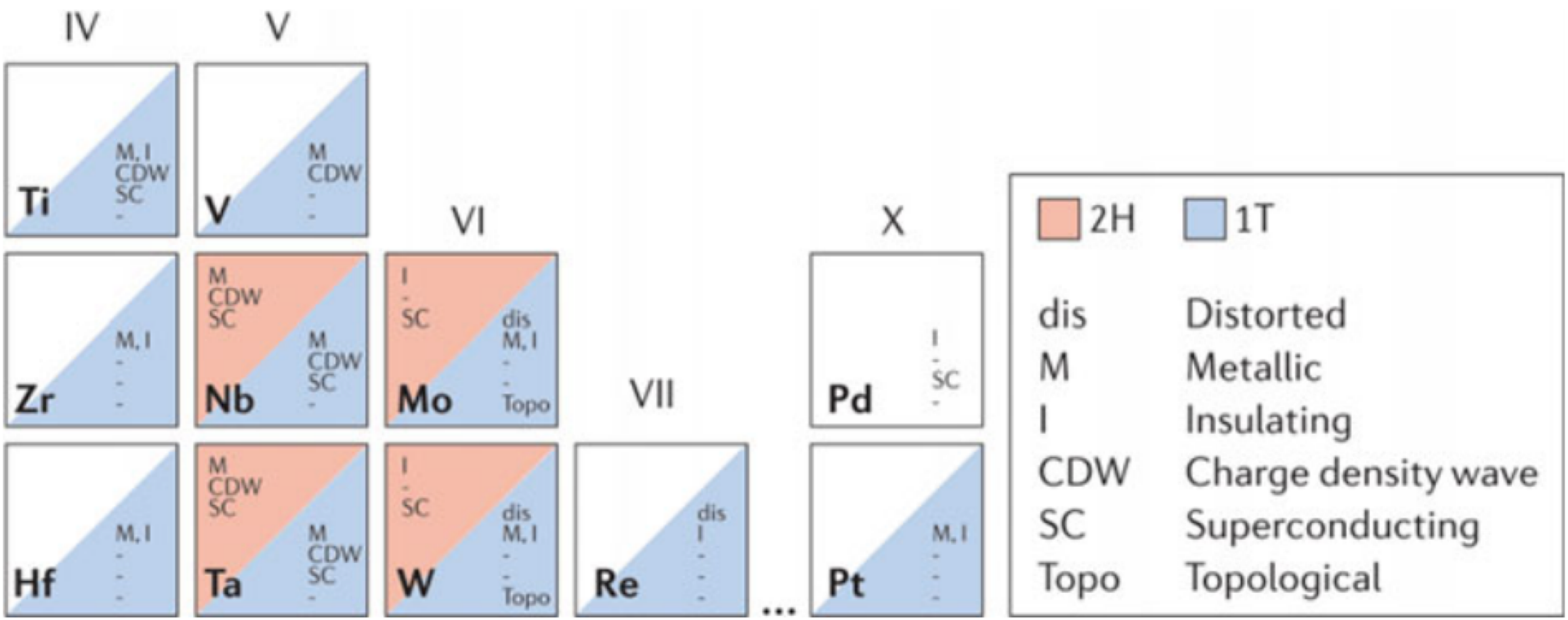
Novoselov *et al.*, PNAS (2005)

1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

2D: Transition metal dichalcogenides (TMDs)

Properties of TMDs



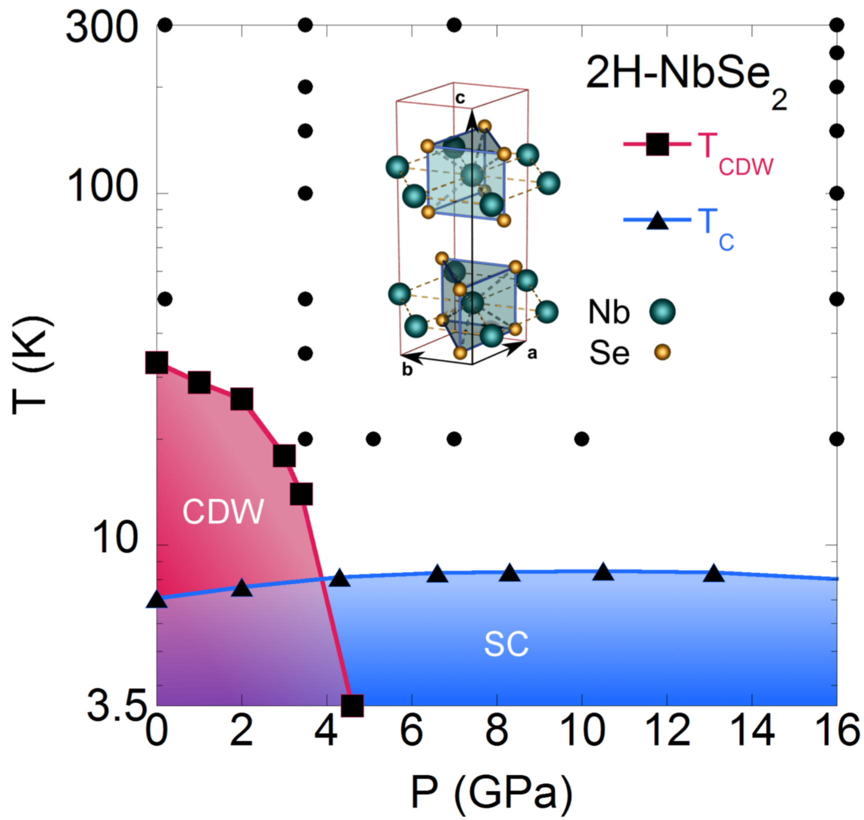
N. Sabari Arul and V. Devaraj Nithya., "Two Dimensional Transition Metal Dichalcogenides" (2019)

1. Length scales and low dimensional systems

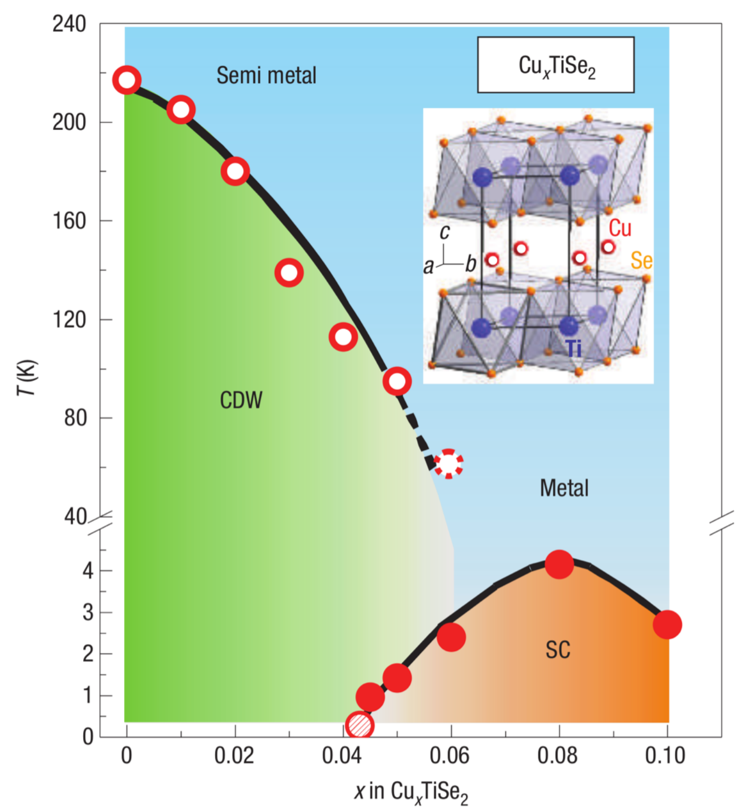
1.4 Examples of low-dimensional systems

2D: Transition metal dichalcogenides (TMDs)

Metallic TMDs phase diagrams with charge-density waves (CDWs) and superconductivity (SC)



Leroux *et al.*, PRB (2015)



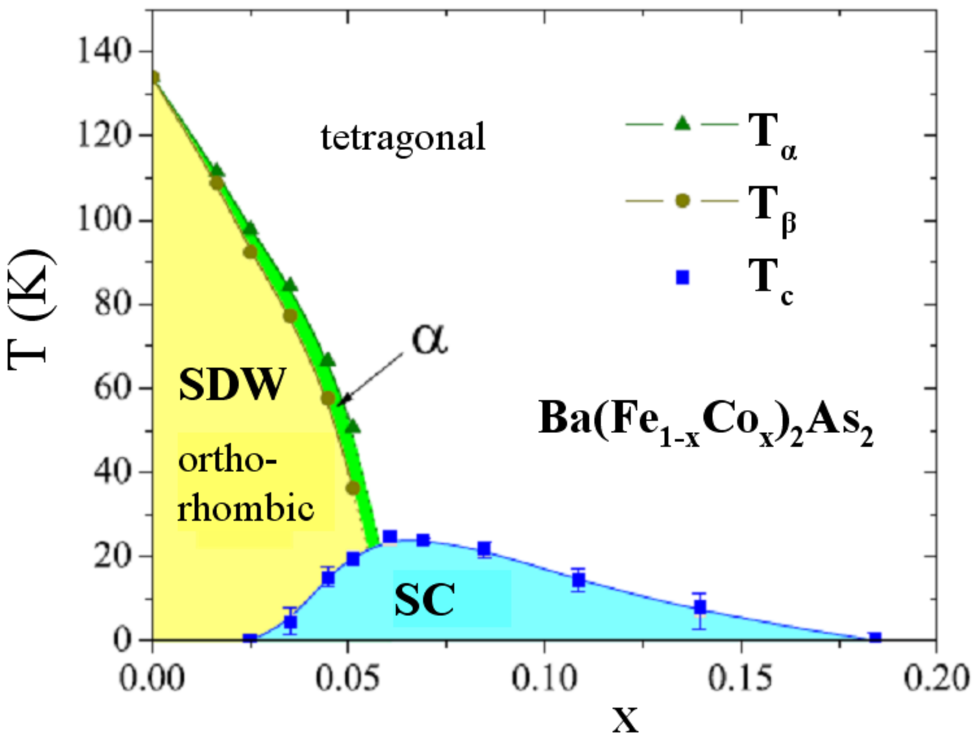
Morosan *et al.*, Nat. Phys. (2006)

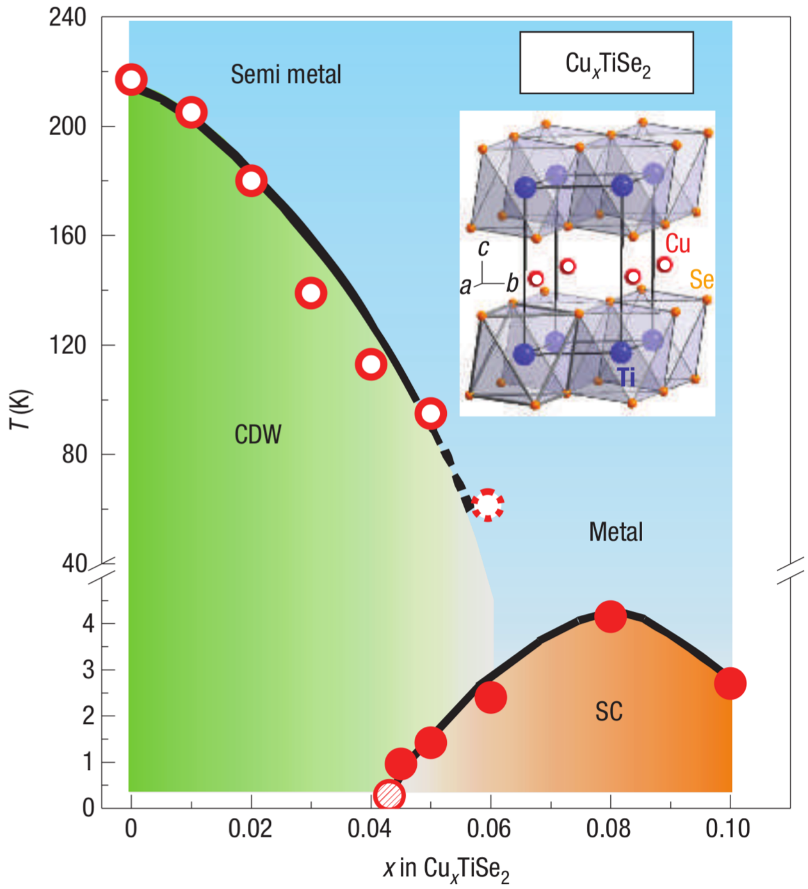
1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

2D: Transition metal dichalcogenides (TMDs)

Similar phase diagram to the high-temperature superconductors





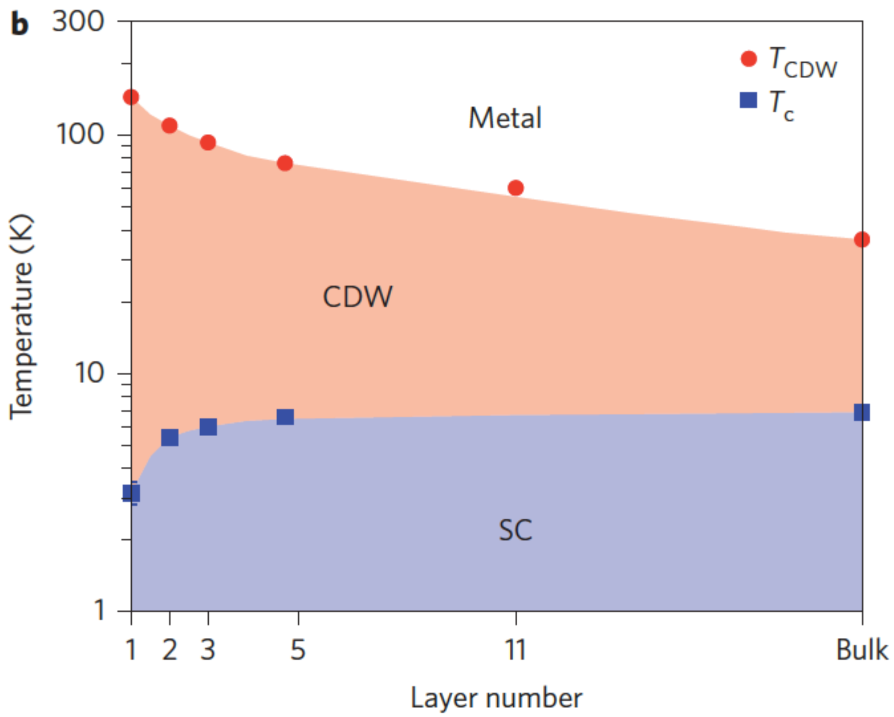
1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

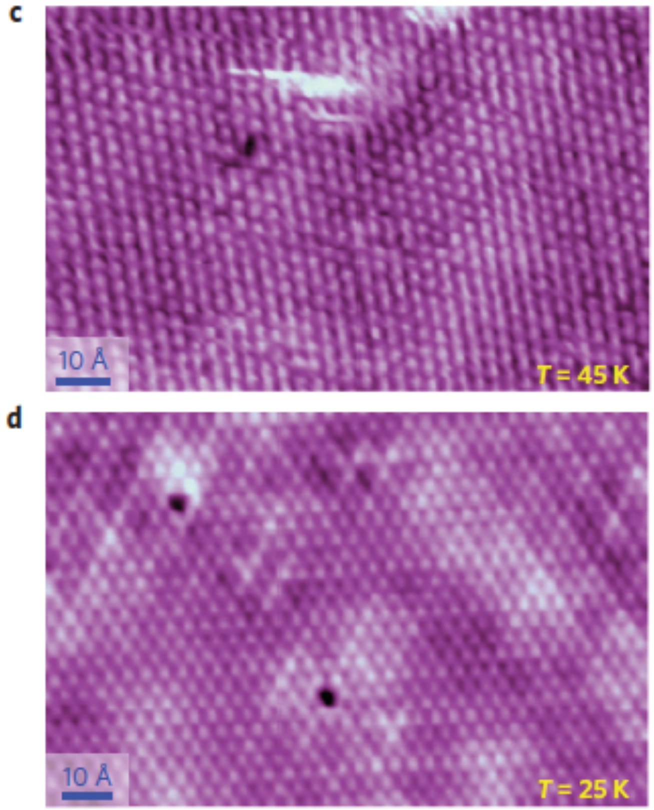
2D: Transition metal dichalcogenides (TMDs)

Contradicting results about the CDW temperature in the 2D limit

$NbSe_2$

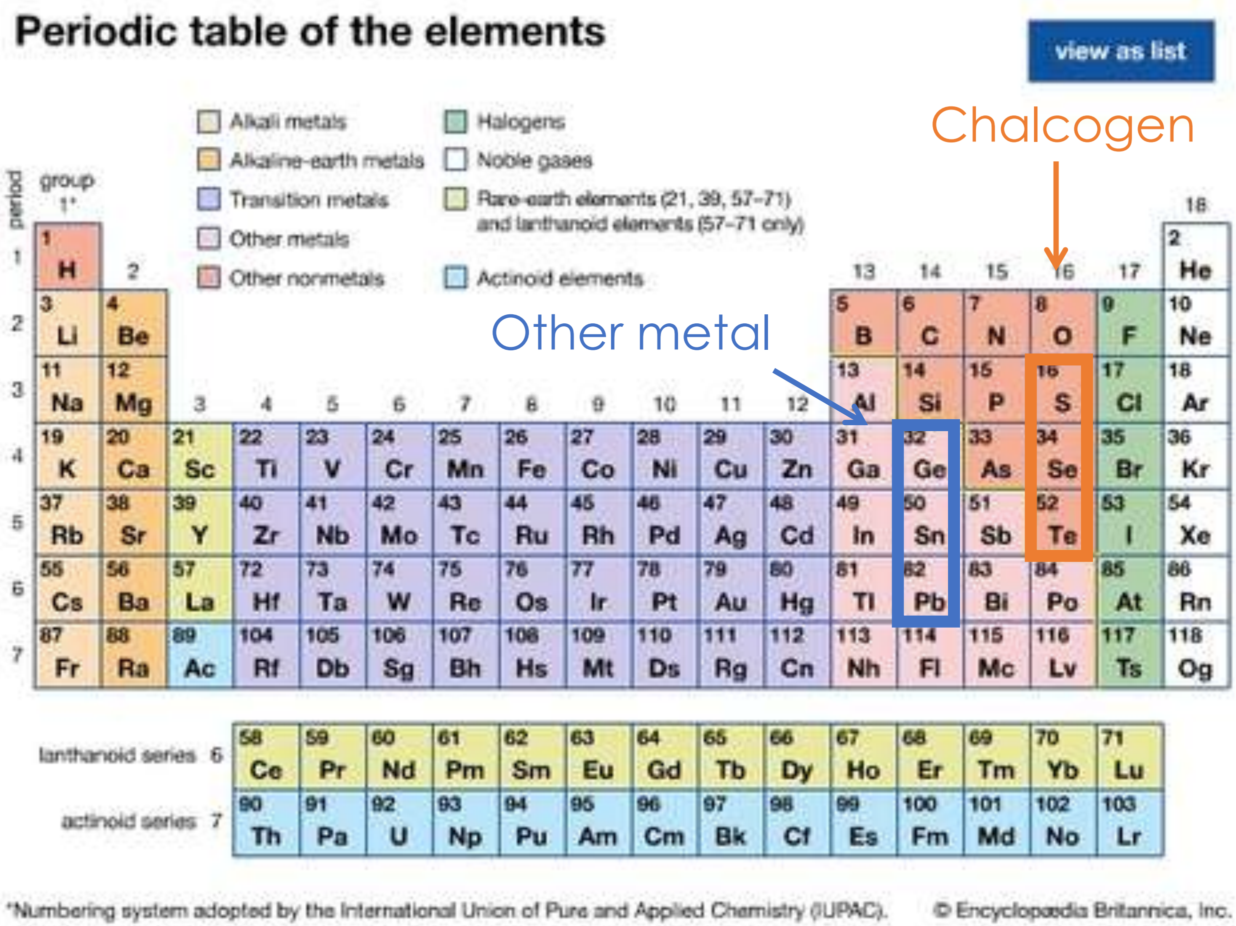


Xi *et al.*, Nat. Nanotech. (2015)



Ugeda *et al.*, Nat. Phys. (2015)

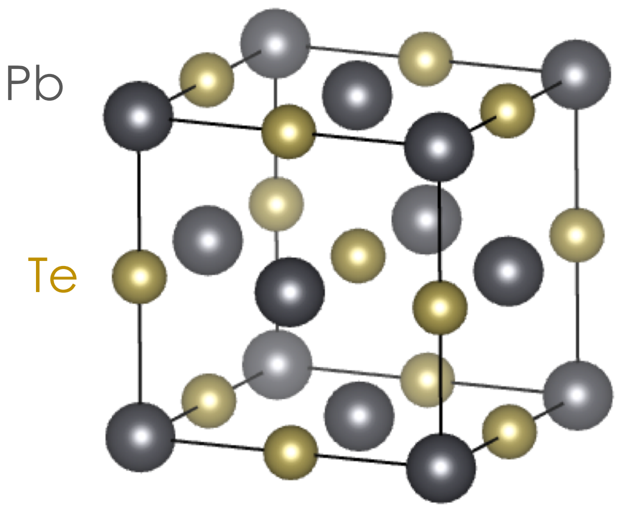
2D: Semiconducting chalcogenides



2D: Semiconducting chalcogenides

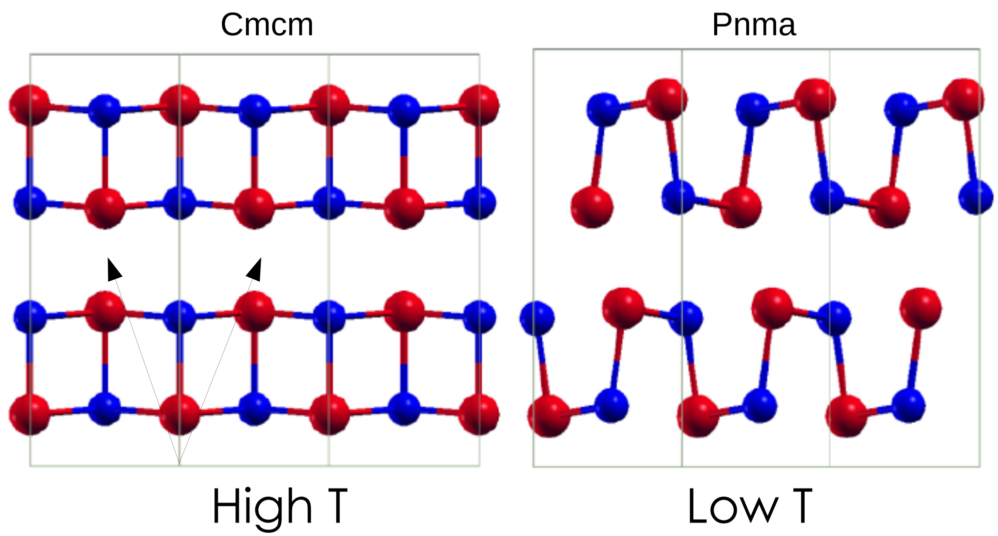
Crystal structures and phase diagrams

PbTe



Rock-salt structure

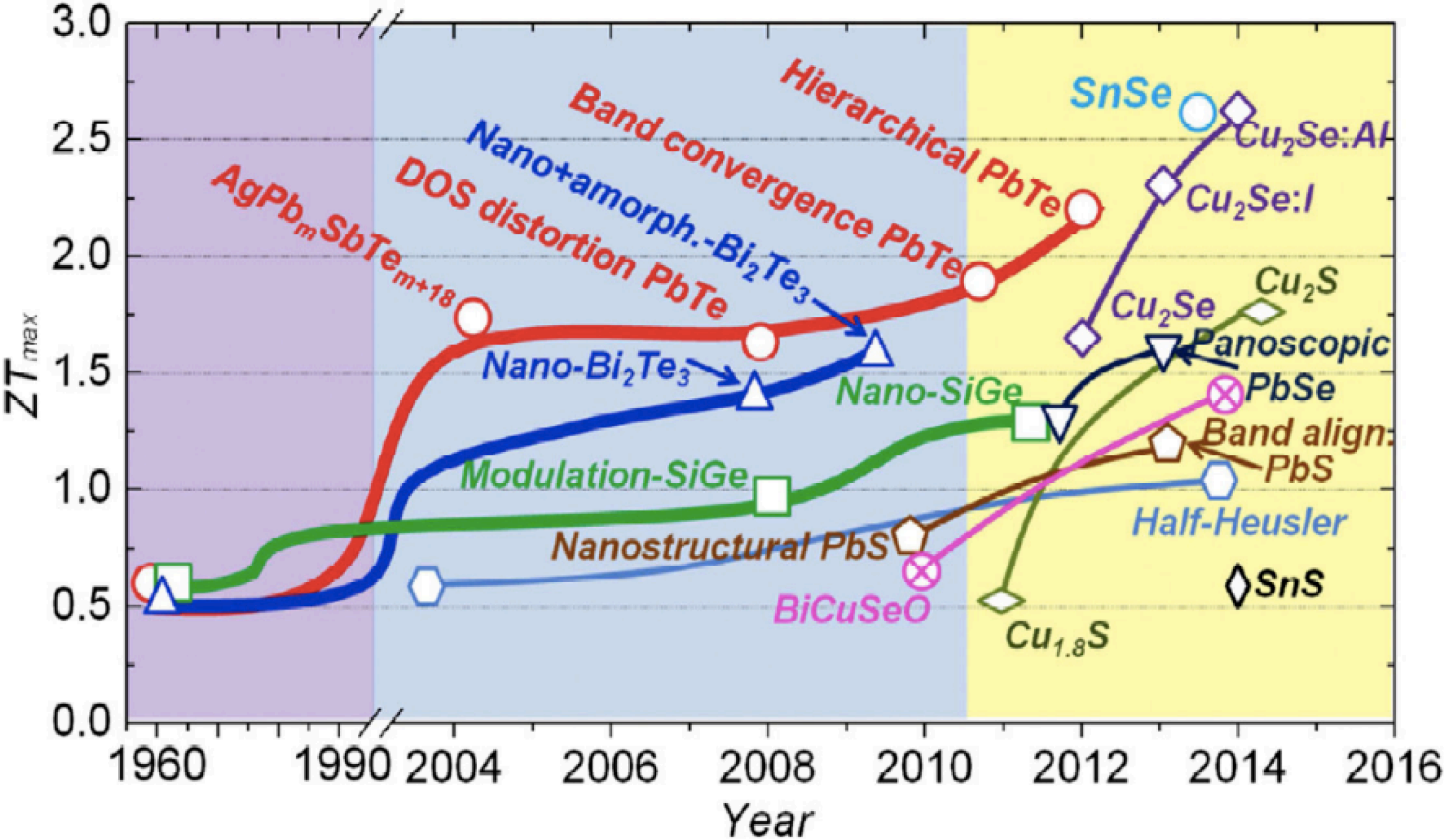
SnSe



Distortions of rock-salt structure

2D: Semiconducting chalcogenides

Very good thermoelectric materials



2D: Semiconducting chalcogenides

Synthesized in the 2D limit and possible ferroelectricity

REPORTS

FERROELECTRICITY

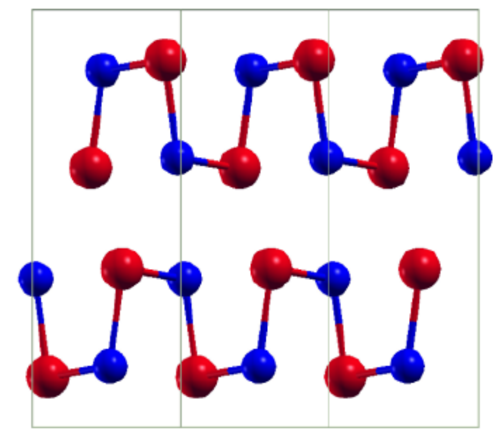
Discovery of robust in-plane ferroelectricity in atomic-thick SnTe

Kai Chang,[1,2]* Junwei Liu,[3,1,2]* Haicheng Lin,[1,2] Na Wang,[1,2] Kun Zhao,[1,2] Anmin Zhang,[4] Feng Jin,[4] Yong Zhong,[1,2] Xiaopeng Hu,[1,2] Wenhui Duan,[1,2] Qingming Zhang,[4,5] Liang Fu,[3] Qi-Kun Xue,[1,2] Xi Chen,[1,2]† Shuai-Hua Ji[1,2,6]†

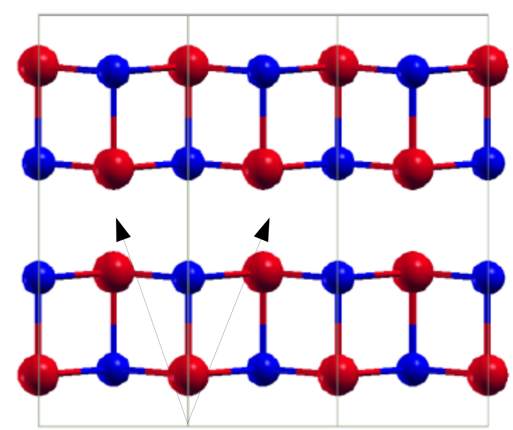
Stable ferroelectricity with high transition temperature in nanostructures is needed for miniaturizing ferroelectric devices. Here, we report the discovery of the stable in-plane spontaneous polarization in atomic-thick tin telluride (SnTe), down to a 1–unit cell (UC) limit. The ferroelectric transition temperature T_c of 1-UC SnTe film is greatly enhanced from the bulk value of 98 kelvin and reaches as high as 270 kelvin. Moreover, 2- to 4-UC SnTe films show robust ferroelectricity at room temperature. The interplay between semiconducting properties and ferroelectricity in this two-dimensional material may enable a wide range of applications in nonvolatile high-density memories, nanosensors, and electronics.

Science (2016)

Pnma



Cmcm



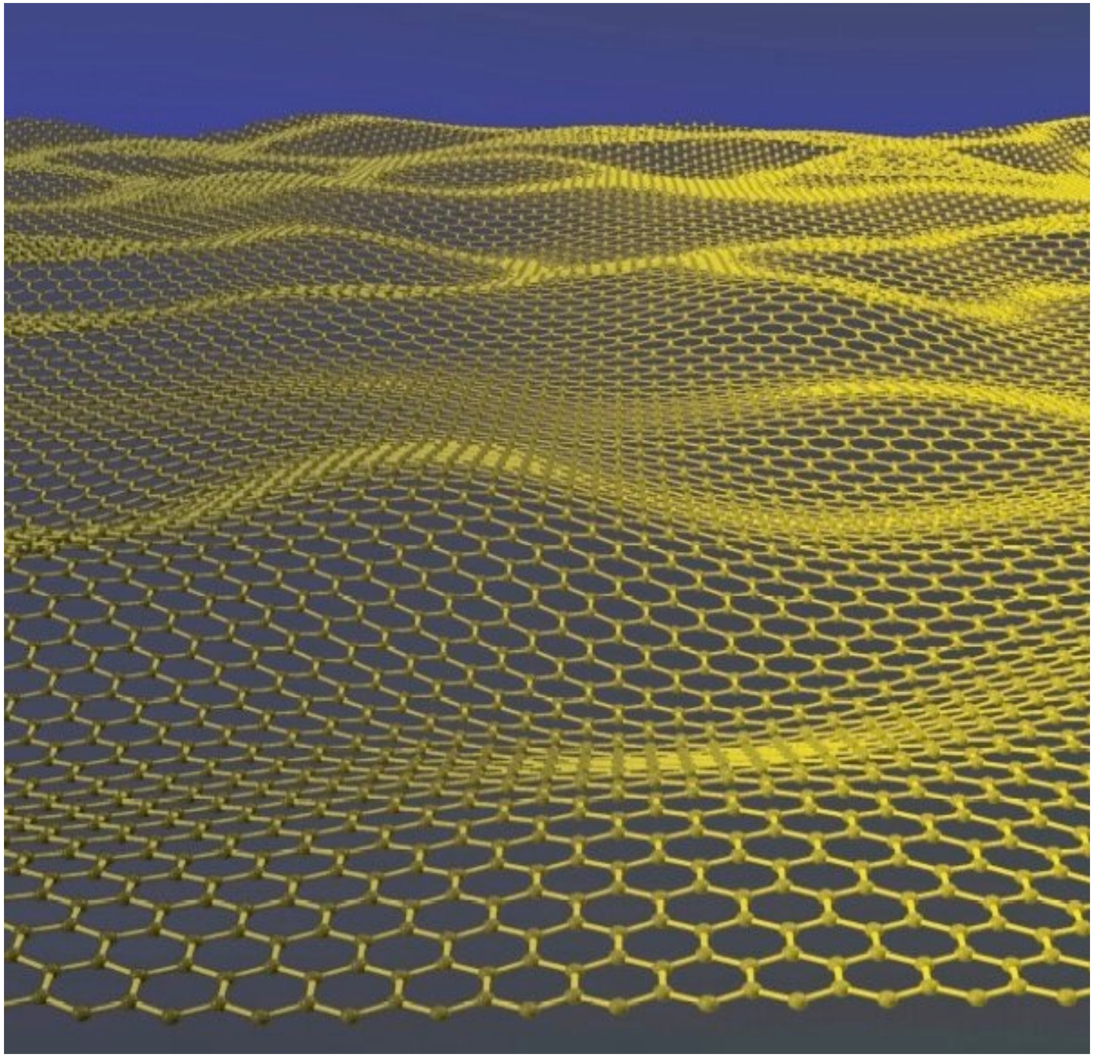
2D: Graphene

A. Geim

K. Novoselov

Nobel Prize Physics 2010

"for groundbreaking experiments regarding the two-dimensional material graphene "

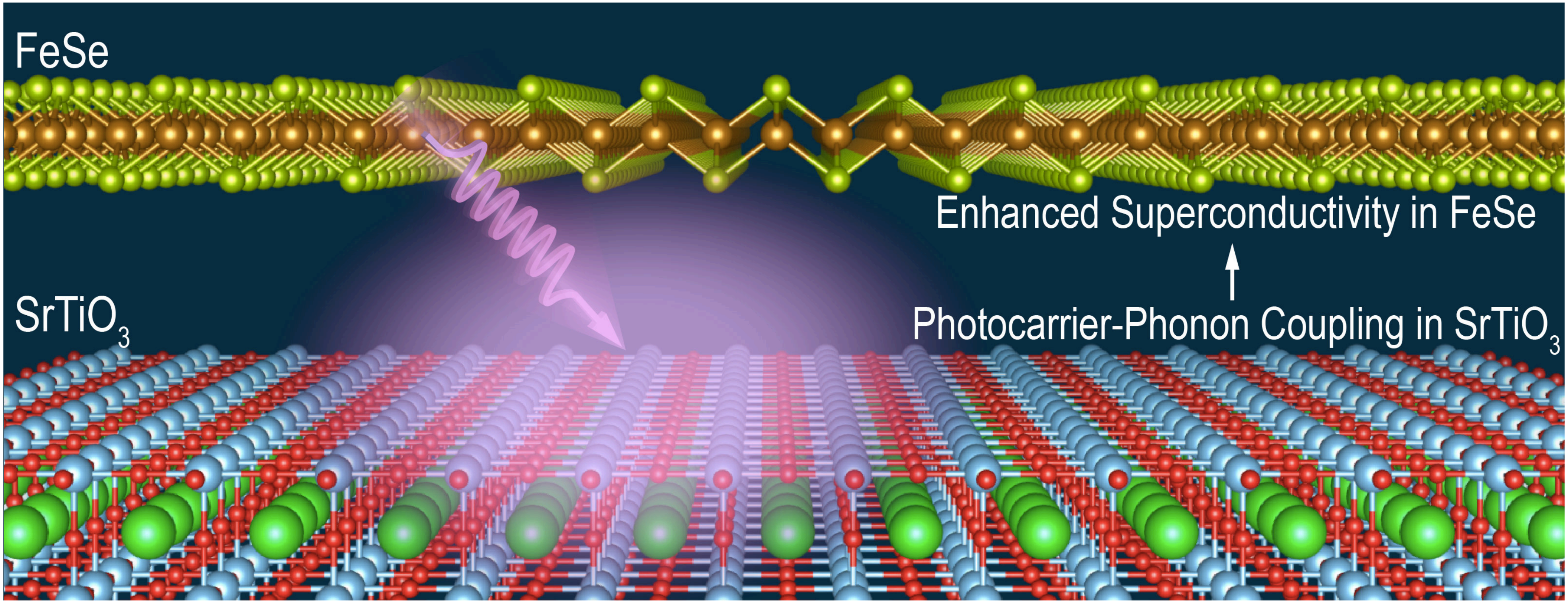


1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

2D: FeSe

- Superconductivity in bulk FeSe at 9K
- On monolayer on top of $SrTiO_3$ at 65-109K

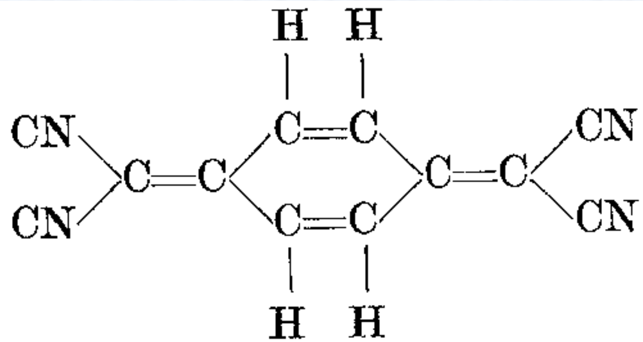


1. Length scales and low dimensional systems

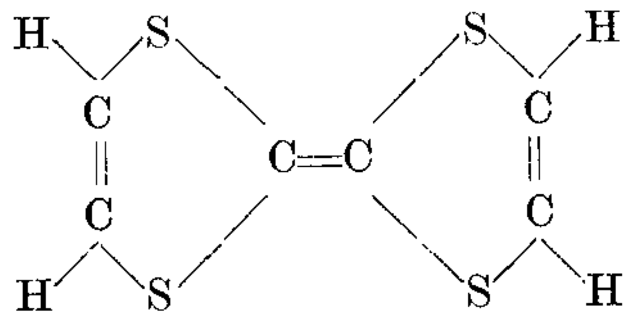
1.4 Examples of low-dimensional systems

1D: Polymers and organic molecules

TCNQ molecule

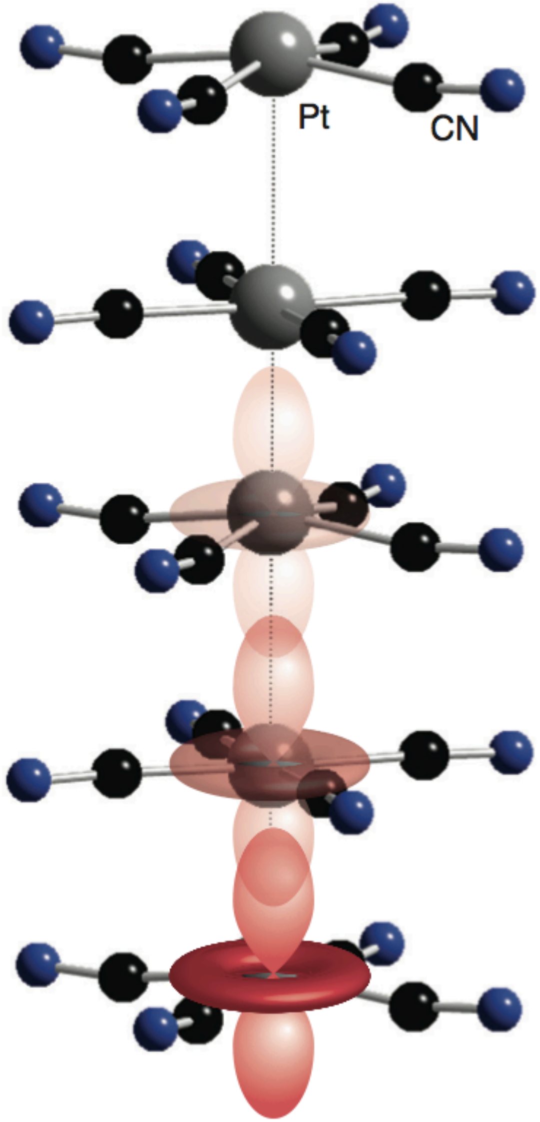


TTF molecule

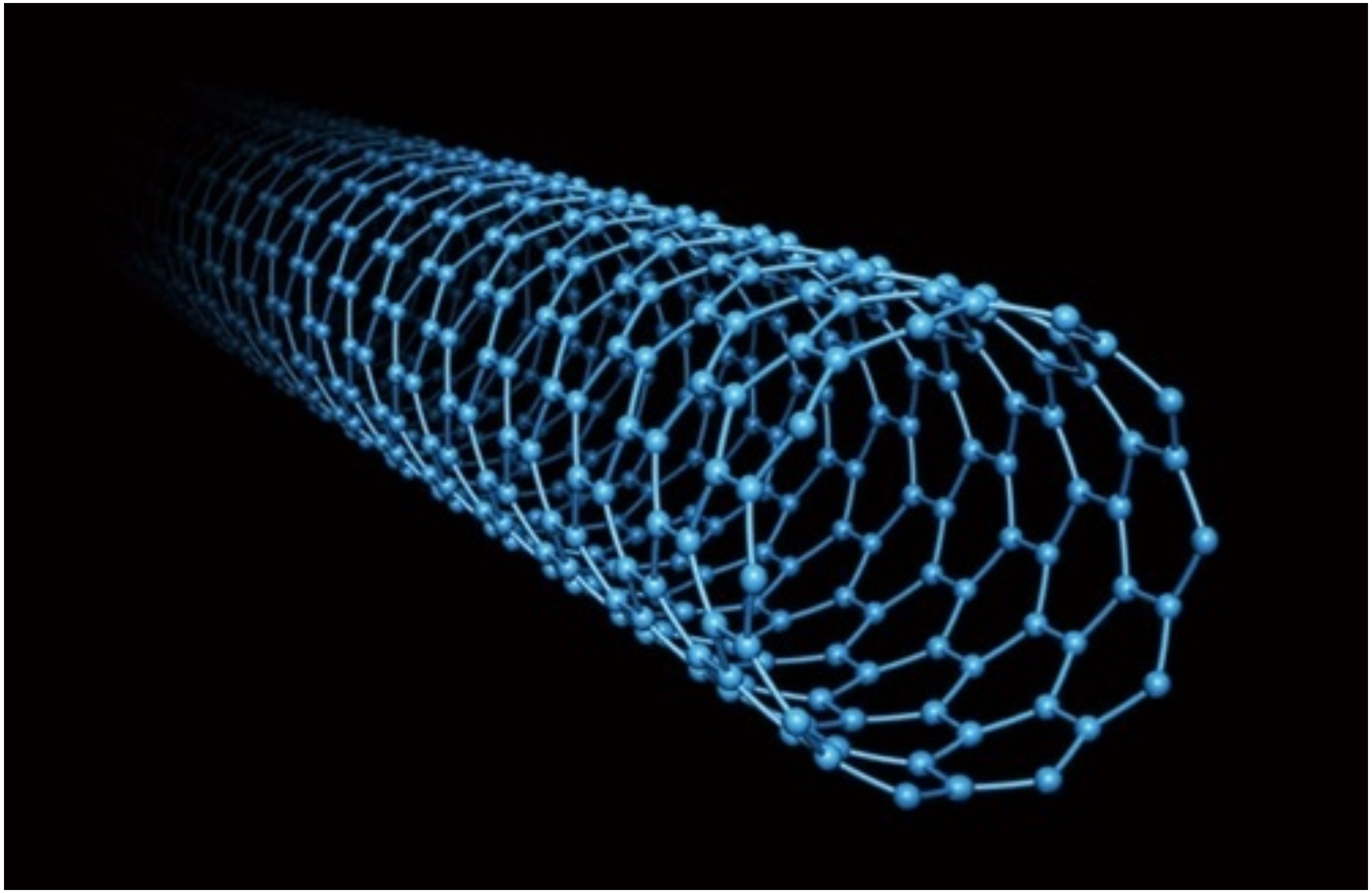


1D: Inorganic chains

$K_2Pt(CN)_4Br_{0.2}\ H_20$

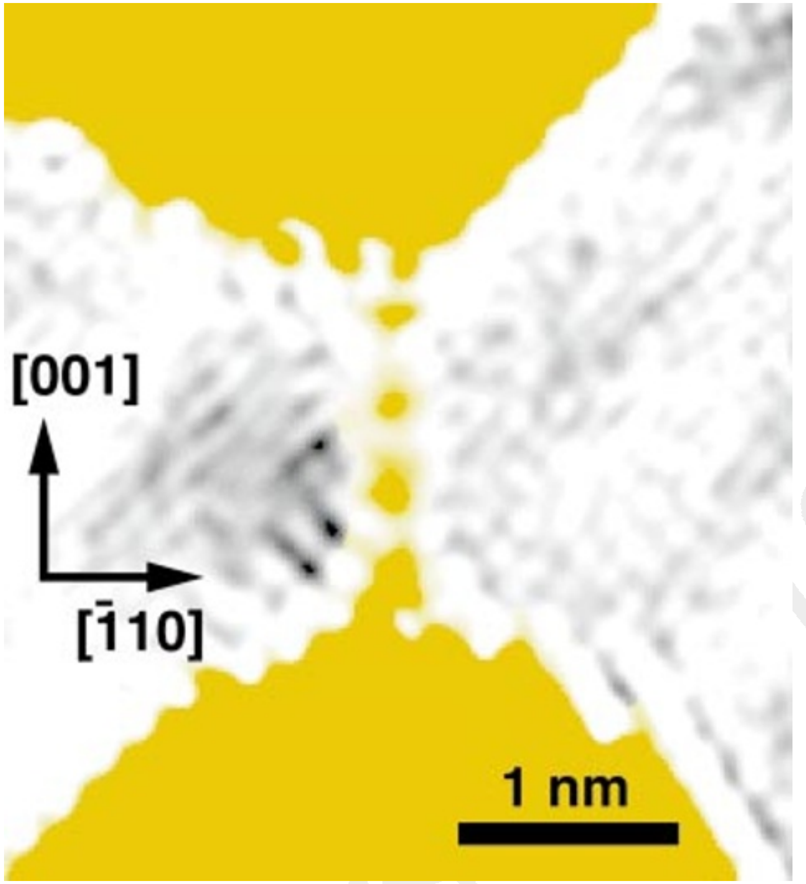


1D: Carbon nanotubes



1D: Metallic wires

Gold wires produced with STM



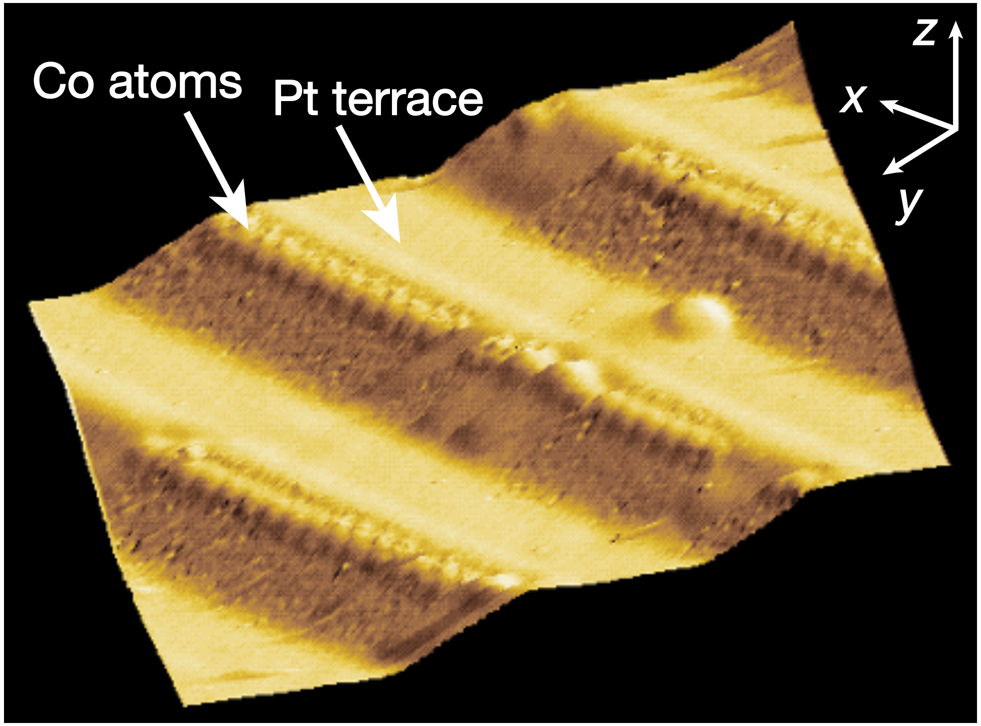
Ohnishi *et al.*, Nature (1998)

1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

1D: Nanowires on surfaces

Ferromagnetic one-dimensional monatomic metal chains



Gambardella *et al.*, Nature (2002)

1D: Overview of some properties

Table 6.3-1. Quasi-one-dimensional materials (SC: superconductor)
Tr: room temperature
GIC: graphite intercalation compound

compound	peculiarity
1) TTF-TCNQ	Peierls transition
$(TMTSF)_2ClO_4$	$T_c = 1.3$ K SC
$(TMTSF)_2PF_6$	$T_c = 0.9$ K SC (under pressure)
2) KCP	Peierls transition
$K_2Pt(CN)_4Br_{0,2} \cdot H_2O$	
3) $Hg_{2,86}AsF_6$	SC
4) $(SN)_x$	$T_c = 0.33$ K
$(SNBr_{0,4})_x$	$T_c = 0.35$ K
	$3D$-SC
5) $(CH)_x \cdot SbF_5$	Peierls transition
6) $(=C=)_x$	α-Carbyne
$(-C{\equiv}C-)_x$	β-Carbyne
7) TaS_3	Peierls transition
$NbSe_3$	
8) graphite	semi-metal
GIC (SbF_5)	two-dimensional
GIC (AsF_5)	
GIC (C_8K)	$T_c = 0.2$ K SC
9) copper	metal
aluminium	metal
	three-dimensional

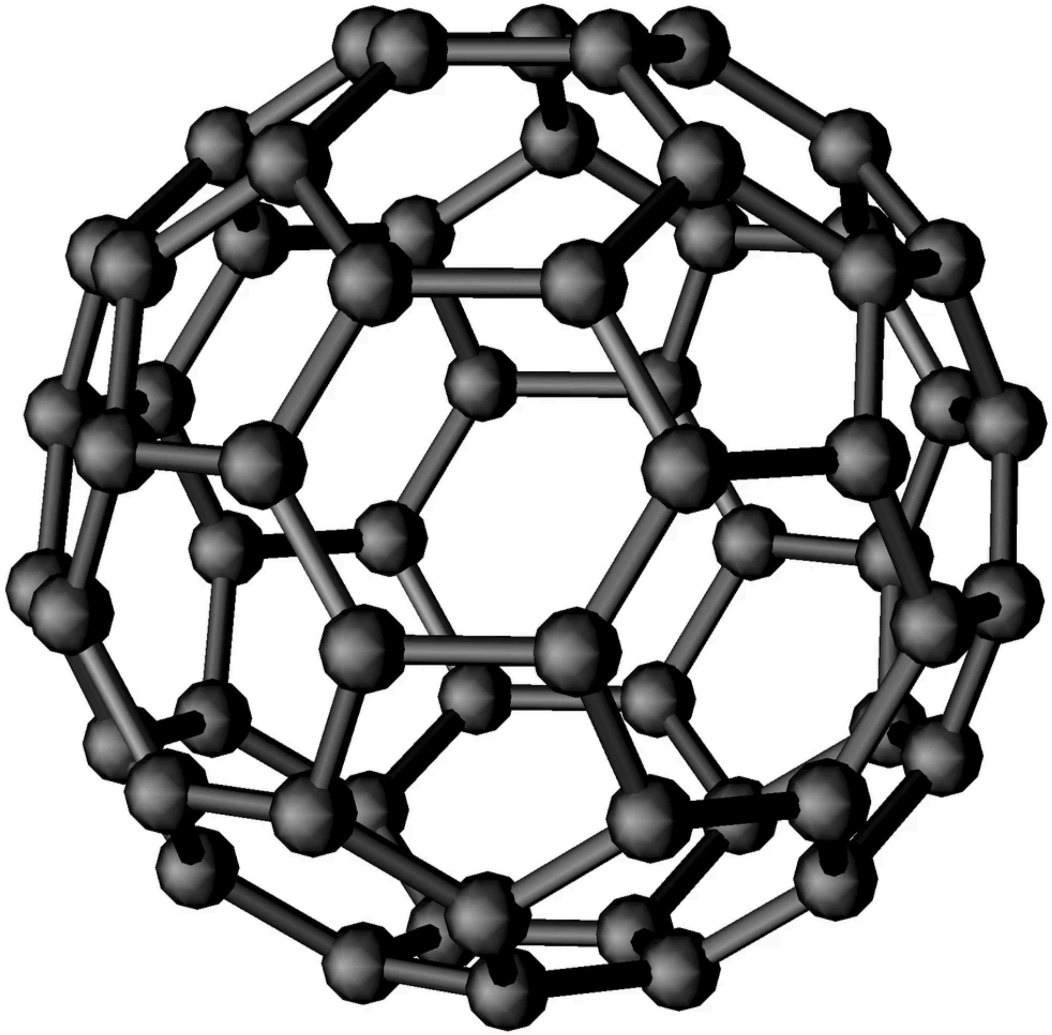
G. Lehmann, P. Ziesche, "Electronic properties of metals" 1990

1. Length scales and low dimensional systems

1.4 Examples of low-dimensional systems

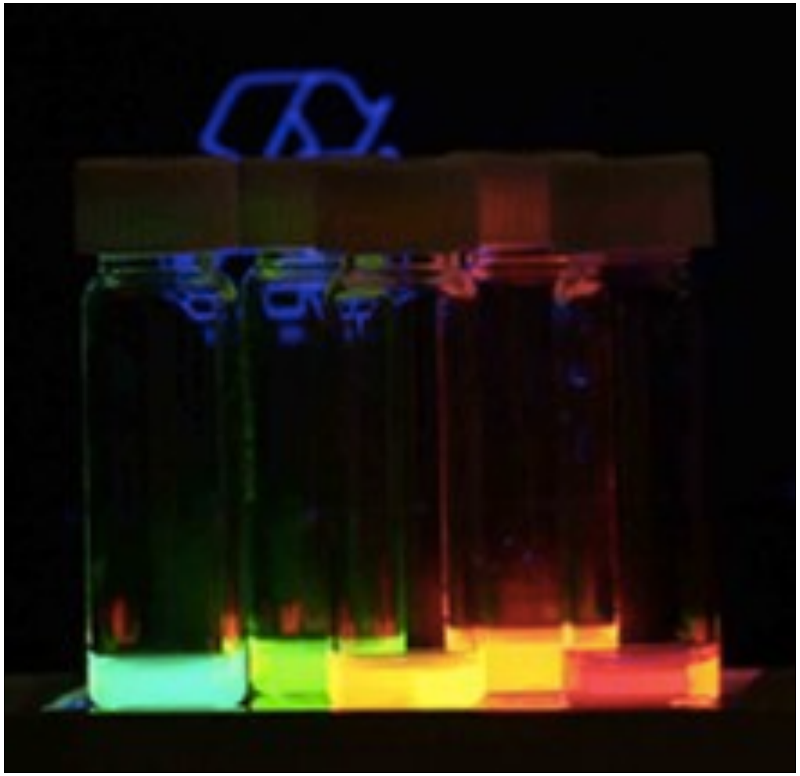
0D: Fullerenes

C_{60}



0D: Quantum dots

- Semiconducting particles of few nanometers
- Also called artificial atoms
- Size dependent properties

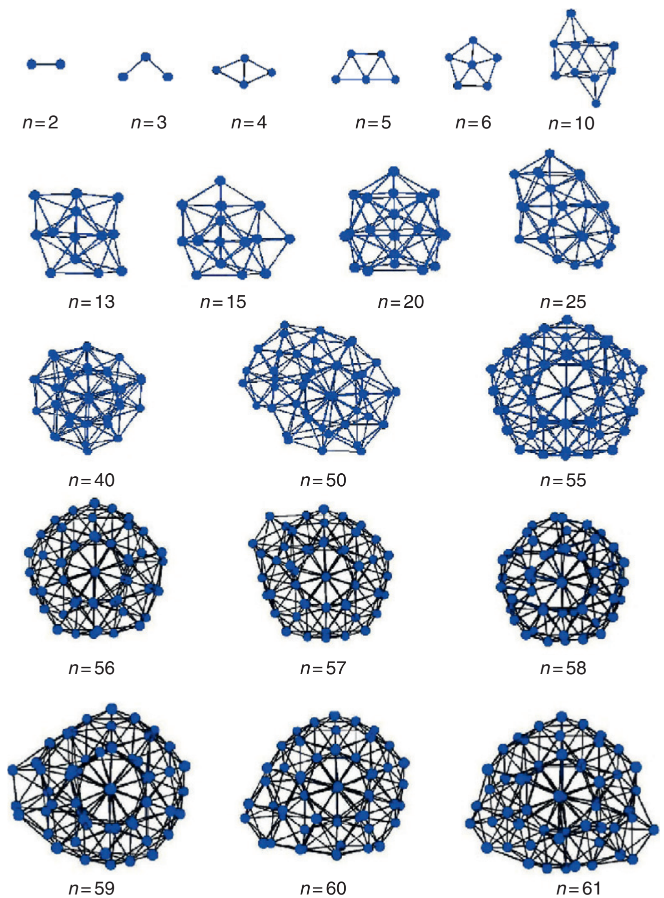


0D: Atomic clusters

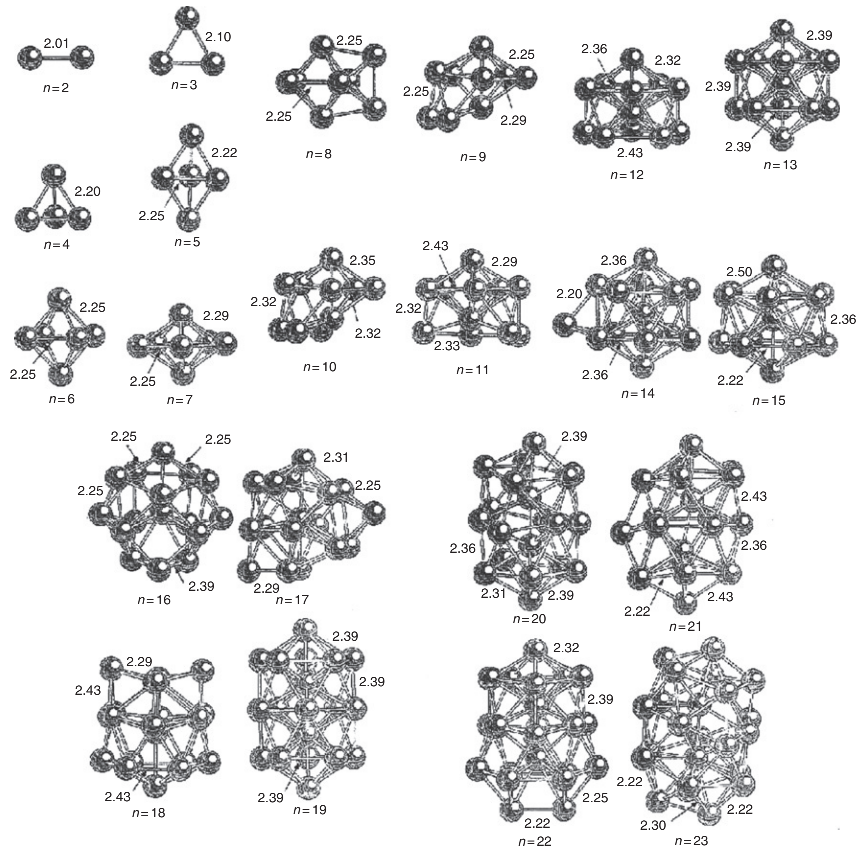
- Clusters can be formed when a hot plume of atoms or molecules in a gas are cooled by collision with rare-gas atoms much as droplets of water are formed when hot steam cools and condenses

0D: Atomic clusters

Na clusters



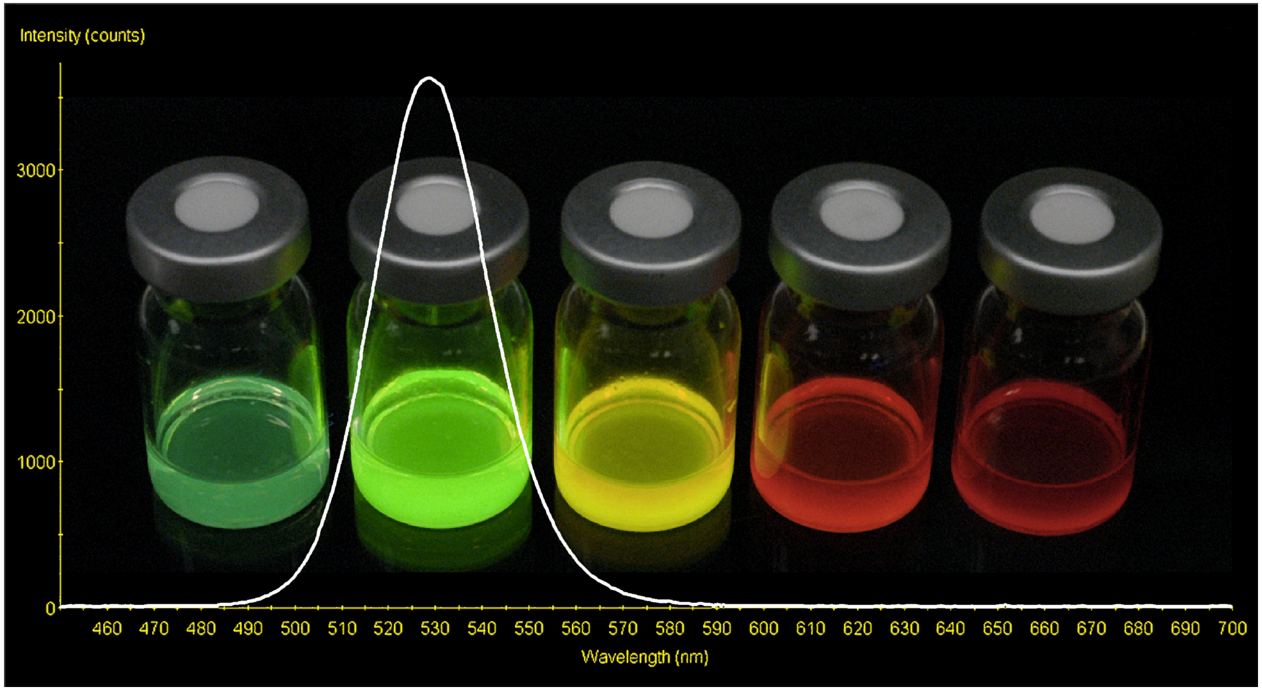
Ni clusters



P. Jena and A. W. Castleman, “Introduction to Atomic Clusters” (2010)

0D: Synthetic nanocrystals

- Chemical synthesis of nanoparticles of CdS, CdSe, CuCl
- Size control (from few nm to 200 nm)



Nanolitography

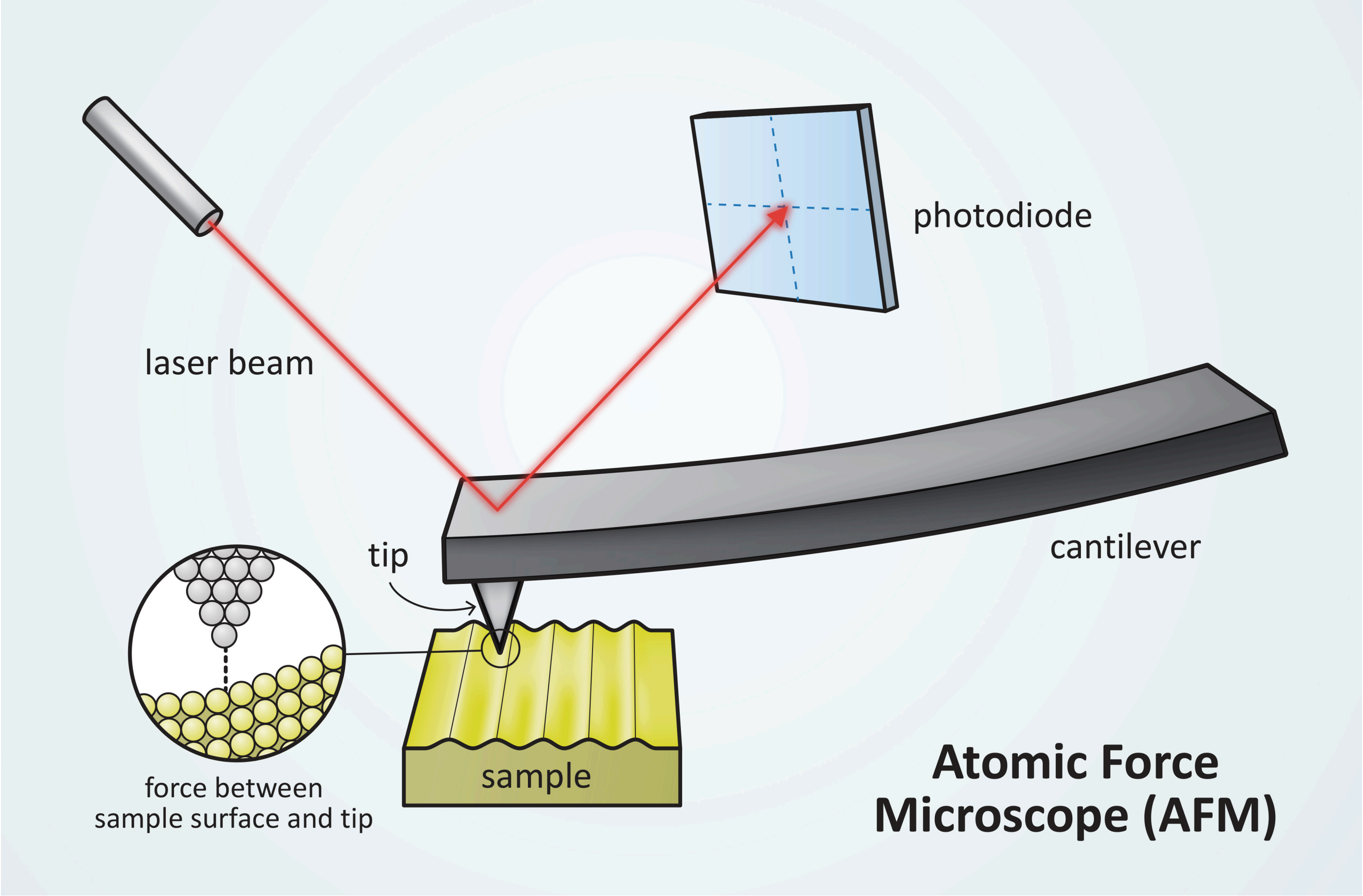
- Techniques for etching, writing, printing at the nanoscale
  - Optical litography
  - Electron-beam litography
  - Scanning proble litography
  - Nanoimprint litography

Nanolitography

https://www.youtube.com/watch?time_continue=189&v=PWV9pvdRBNY&feature=emb_logo

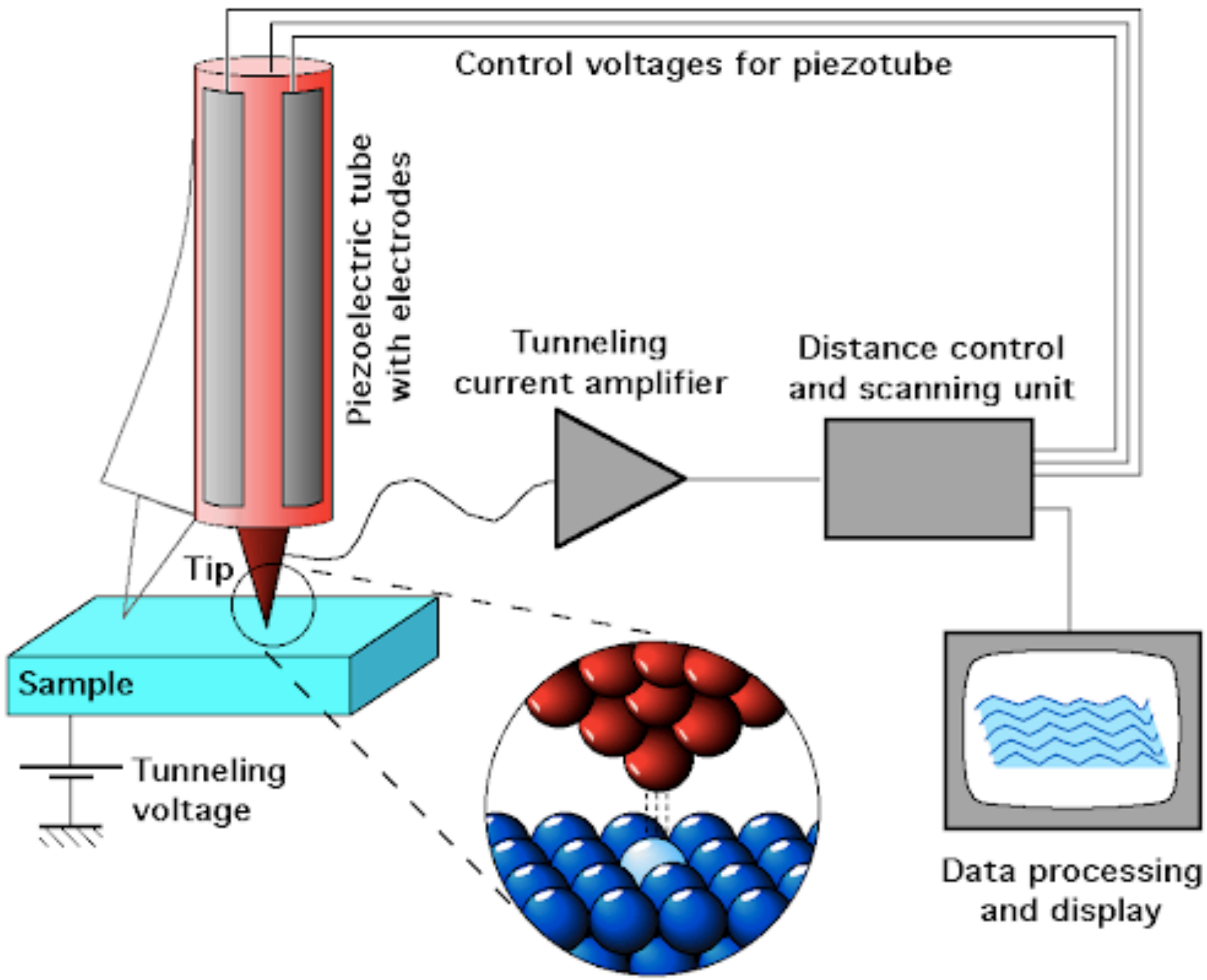
Atomic Force Microscopy (AFM)

- Detects the fluctuations of the tip induced by the forces of the sample
- Can be used for litography



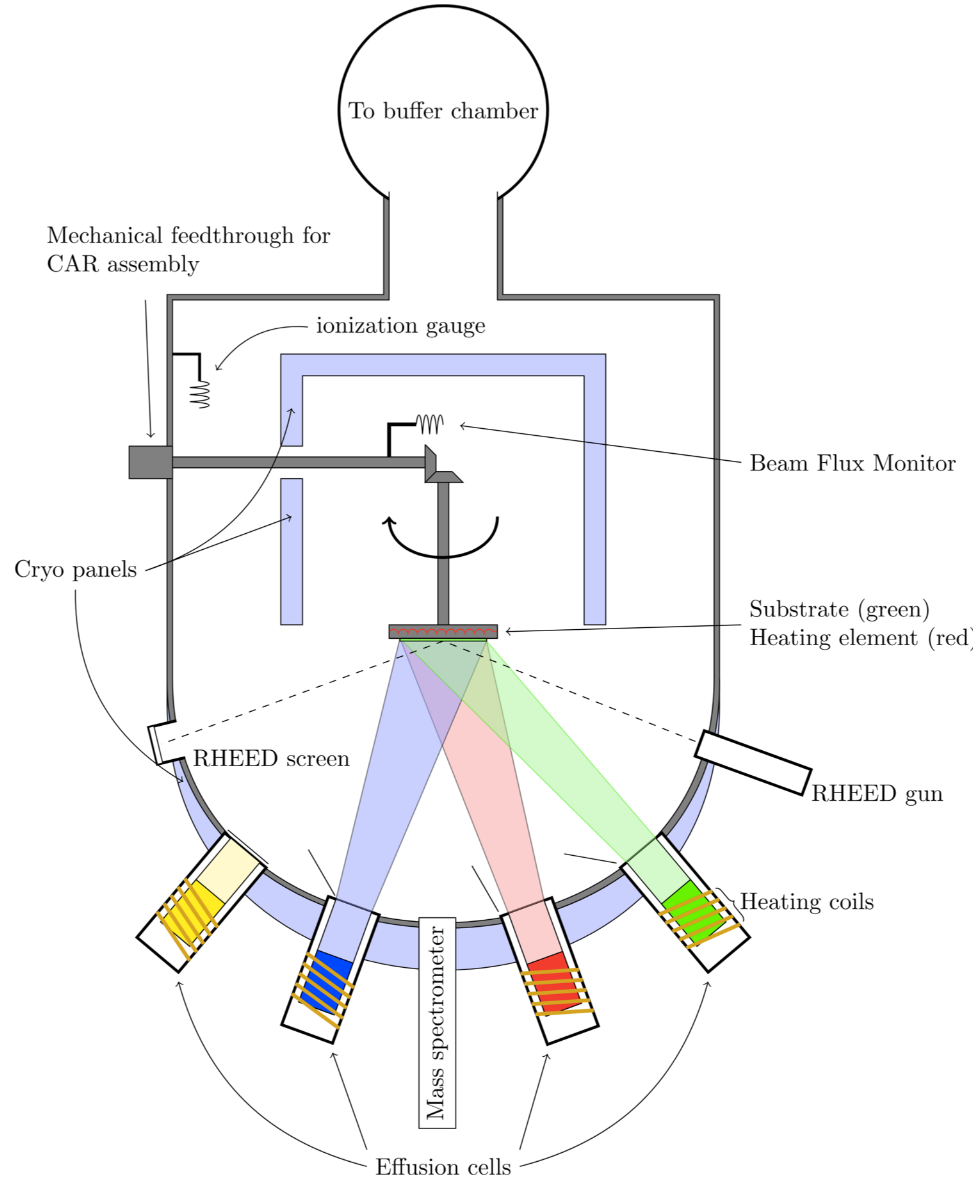
Scanning Tunneling Microscope (STM)

- Controls the current tunneled from the sample to the atomic tip.
- Can be used to image and manipulate individual atoms.
- Atomic resolution.



Molecular Beam Epitaxy (MBE)

- In ultra-high-vacuum conditions molecules or atoms are deposited on surfaces.
- Monolayer, bilayers, etc. can be created
- The samples are later characterized by STM or AFM.



1. Length scales and low dimensional systems

1.6 Exercise

Perform a literature search and find a material that can be synthesized in low dimensions and or in its bulk form it has low-dimensional features.

- Which are the features in its electronic properties that make it behave as a low-dimensional material?
- Is there any other particular property that makes it behave as a low-dimensional system?