Properties of Semiconductors and Related Nanostructures

Spring Semester 2025

- ❑ Introduction to MSE484
  - Introducing the teaching party
  - Course structure: calendar and objective
  - Evaluation: assessment and deadlines
- ❑ Respect EPFL
- ❑ Let's start
  - Topics and Books
  - Class 0: semiconductors and nanomaterials

The Team for this Course

Valerio Piazza
Lecturer

Anja Tiede
Teaching Assistant

Reyhaneh Ramezani
Teaching Assistant

Ludovica Lunghi
Teaching Assistant

Course Overview

<u>5 ECTS</u>: approx. 10h of work/week

(class + individual/group work)

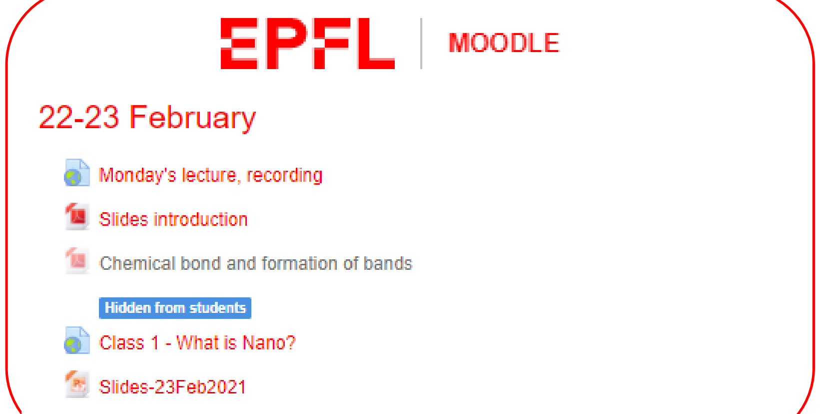
The course is delivered in hybrid mode:

- In Presence
- Online via Zoom
  - **Monday's class, 3:15pm:**
    - https://epfl.zoom.us/j/66654328109
  - **Tuesday's class, 8:30am:**
    - https://epfl.zoom.us/j/62184446677
- On Moodle
  - Supporting material
  - Recordings
  - Assignments

zoom

- Electronic Whiteboard
- Slides

Please, turn your camera on when interacting with the class



Calendar

Block 1 (individual):

Frontal lectures
- 4h/week classes
- Ask & Answer

Numerical Sessions (4 classes)
- Solve Exercises on Moodle
- Clarify Assignments task
- Revise concepts

Debate classes (2 classes)
- Papers on Moodle
- Class discussion

Workshops (2 classes)
- Learn NextNano software
- Improve science communication skills

Block 2 (group):

Group Seminars
- Work together
- Split tasks
- Provide/accept feedbacks

Due:

1 Numerical Assignement
1 Seminar (group)
1 Report

	DATE	CONTENT OF THE CLASS	Notes
B1	17/02 -25/02	Introduction Band Structure (KP model) Effective mass Density of states in bulk and nanostructures Charge carriers statistics and Fermi level	
B1	03/03	Paper Debate 01	
B1	04/03	Exercise Session	Focus on Exercise set 1
B1	10/03 – 17/03	Doping in semiconductors Functional properties: Optics and Electronic transport	
B1	18/03	NextNano Workshop	Class with Reyhaneh
B1	24/03	Exercise Session	Focus on Exercise set 2
B1	24/03, 17h00	Release Assignment	
B1	25/03-01/04	Surface and Interfaces Heterostructures and Devices Bulk optoelectronics: solar cells and LEDs	
B1	07/04	Info Session	Focus on Assignement
B1	08/04	Paper Debate 02	
B1	14/04, 14h00	Deadline Assignment	
B1	14/04	How to present scientific results: Workshop	Class with Ludovica
B1	15/04	Correction Assignment	
B1		Easter Week	
B1	28/04	2D materials	
B2	29/04	Low-dimensional devices	
B2	05/05-20/05	Preparation of seminars (2 meetings with supervisors)	
B2	26/05-27/05	Seminars	
	30/05, 17h00	Reports	

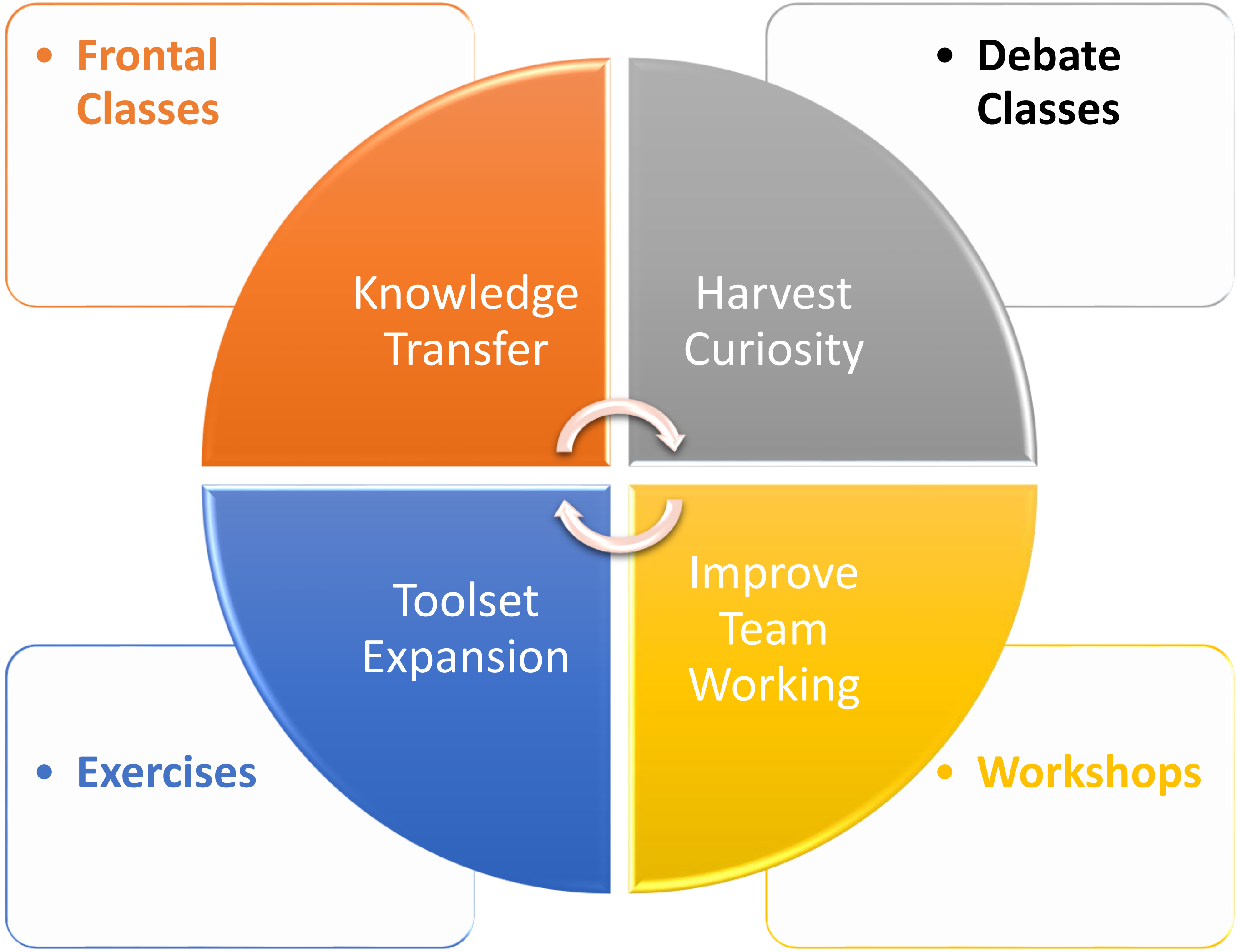
Course Structure

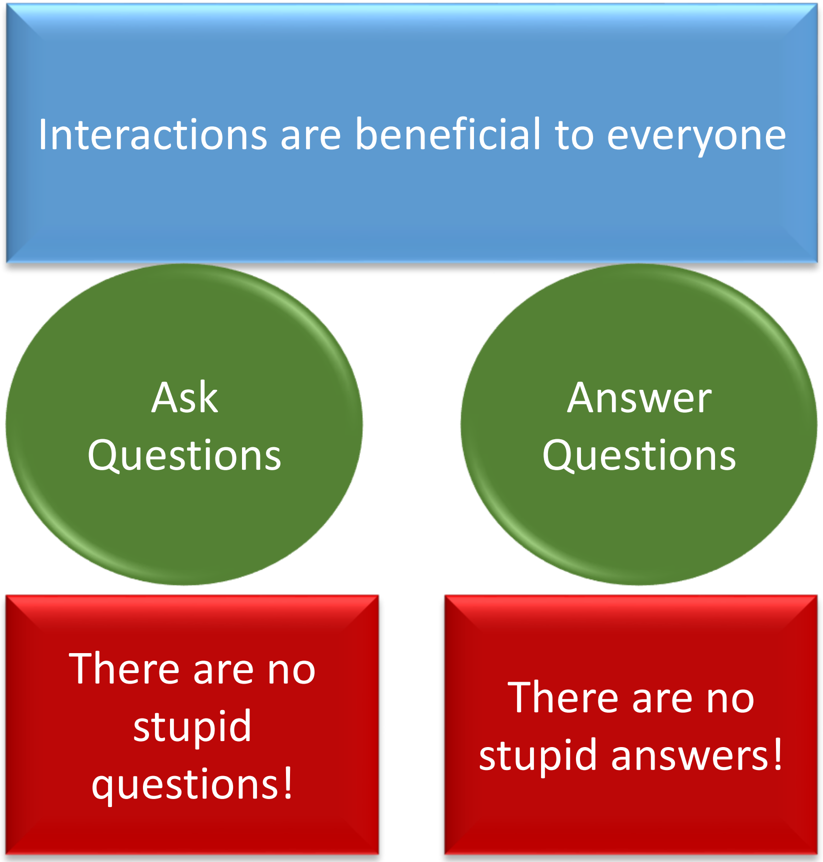
MSE-484 COURSE	
	<u>First part (individual)</u>:
	Frontal lectures
	Exercise sessions
	Debates
	Workshops
	<u>Second part (group)</u>:
	Preparation of seminars: • Meeting with group members • Meeting with supervisor(s) • Presentation of seminars

- **Frontal lectures**
  - Lecturer explains and **<u>ask questions.</u>** Students follow, answer and **<u>ask questions.</u>**
- **Exercise session***
  - Students do homeworks, students discuss homeworks, lecturer explains homeworks.
- **Debates**
  - Students read papers at home, Students discuss papers in class (Lecturer guides discussion if needed)
- **Workshops**
  - Hands-on class on a specific topic lead by one of the TA

<u>* Basic computational code knowledge is required (Python, Matlab, Mathematica)</u>

Course Objectives





Use of Moodle

On Moodle, from us:

- Teaching support material
- Slides and recording links
- Exercises and Assignments

kaltura

Class recordings on kaltura

On Moodle, from you:

- Upload the Assignments before the deadline

Assignments

- Assignement
  - Released 3 weeks before the deadline. Do not hesitate to touch base by email if the exercise text is unclear.
  - The deadline is important. Short delays will be tolerated (with a significant point reduction). Long delays won't (correction will be done in class the day after the deadline).
- Info Session
  - You can use to work on the Assignments under the supervision of the TAs.
  - TAs **WILL NOT** give you answers on the exercises. Instead they will listen to your reasoning and your doubts and direct you towards the right path, if needed. TAs will clarify unclear/misleading exercise phrasing for the entire class
- Correction Class
  - The procedure to solve the exercise is discussed. If time does not allow, some points will be explained very briefly (priority to exercises with higher conceptual density).

Correction

Answer evaluation

The answer suggests a perfect understanding of the physical system	100%	To be noted: "The answer" refers to both mathematical/numerical operation and written comments. This evaluation is subjective to the teacher and/or the TAs
The answer addresses fairly good the request	90%	
The answer is barely sufficient to address the request	75%	
The answer is barely sufficient to address the request. It also contains unrelated information which are absolutely correct.	75%	
The answer is not sufficient to address the request	50%	
The answer is wrong and it suggests a poor undestanding of the physical system	25%	
The answer is entirely unrelated to the request	0%	

Correction

PLEASE NOTE: If your errors are more «creative» than what we can anticipate, we are still allowed to remove points.

		Common errors	MALUS
A		Numerical error	
	1	Error in calculation	-0.05
	2	Error in code	-0.05
	3	Wrong result, arising from a previous error	0
	4	Nonsense result, arising from a previous error	See conceptual errors
	5	Wrong formula	See conceptual errors
	6	Wrong units	-0.1
	7	No unit	-0.15
	8	No unit repeated (each)	-0.05
B		Representation error (plots and figures)	
	1	Wrong axis	-0.1
	2	Missing axis title	-0.05
	3	Missing axis unit	-0.15
	4	Missing plot/figure caption	-0.025
	5	Missing reference in the main text	-0.025

C		Typos/mispelling	
		Systematic on key terms	-0.1
		Min three times on key terms	-0.05
		All the others	0
D		Conceptual errors	
	1	Result with no physical meaning WITHOUT comment	-50%
	2	Result with no physical meaning WITH associated comment	0
	3	Use of wrong formulas consistently	-100%
	4	Assignment misunderstanding	-25%

If you have any doubts, we can discuss it in class

Seminars

General rules

- Each presentation should last 15-20 minutes
- The presentation must be fractioned among group members
- People belonging to the same group can obtain different grades
- Pay attention to the all the presentations
  - Fill a survey during the presentation of your classmates
  - Everyone has to write a short report on the presentations from the other groups (max 1 page for each seminar)

Details about the seminars (topic, maximum duration, schedule…) will be given by email during the course

Seminars Topics (Examples from 2024)

SEMINAR TOPICS	Student 1	Student 2	Student 3	Student 4	Supervisor
Magic angle in graphene					
Quantum dots for photonic quantum information technology					
Influence of geometry on charge transport in Si nanowires					
Photon emission mechanisms in WS_2					
Diluite nitride photodetectors					
Direct bandgap in h-Ge and h-SiGe					
LCA of PV technologies					
Nanowires for flexible LEDs					

If you want to propose a topic, don't hesitate to reach out to discuss.

Grading

Minimum grade to pass the course: 4.0/6.0

Evaluation will NOT be performed through a single final exam.
The grade wil be given as a weighted average over 3 assignments

Assignment 1	Assignment 2	Assignment 3
Numerical Exercises	**Seminar Presentation**	**Seminar Reports**
50%	**30%**	**20%**

There won't be any minimum grade for each individual block.
(However, we hope that you all will get at least the minimum grade in all the blocks)

HANDWRITING ASSIGNMENTS ARE HIGHLY DISCOURAGED.
If you upload handwritten assignment, we could ask to provide a digitally written document (word, pdf) within 48h after the deadline.

Course Evaluation

In EPFL we are committed to continuing to improve the quality of our courses. Hence, we ask students for feedback on their courses in a number of ways:

- All courses have a short indicative feedback during week 5 each semester — **Week 5**
- All courses also get more detailed in-depth feedback at the end of the semester or after the exam. — **Around (Week 13)**

Mid-semester

What happens to the indicative feedback students provide?

Feedback goes first to the teacher. The teacher should then discuss the feedback with your class, and decide what actions they would like to take to improve the course.

The section that offers the course can also see the indicative feedback.

We appreciate the time and effort which students put into providing useful feedback to their teachers. If you have any questions about the indicative feedback system, please ask your class delegate or section adjoint. If you have any technical questions about the operation of the feedback within IS-Academia, please contact 1234@epfl.ch.

End of the semester

What happens to the in-depth feedback

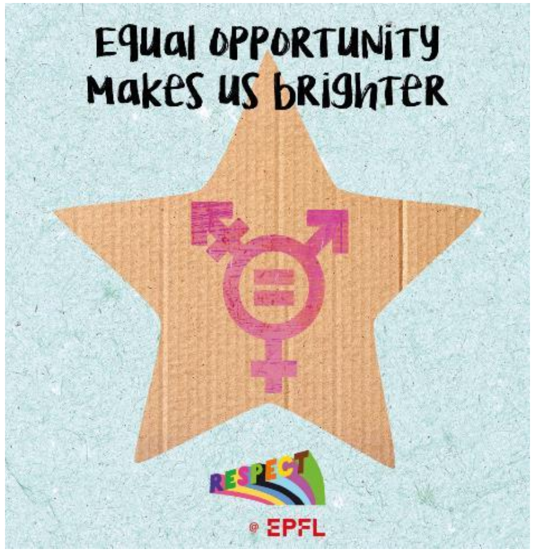
The aggregated and anonymised feedback goes to the teacher and to the section providing the course. Based on the feedback specific actions may be taken and additional support might be provided to the teacher to help improve the course for the next semester.

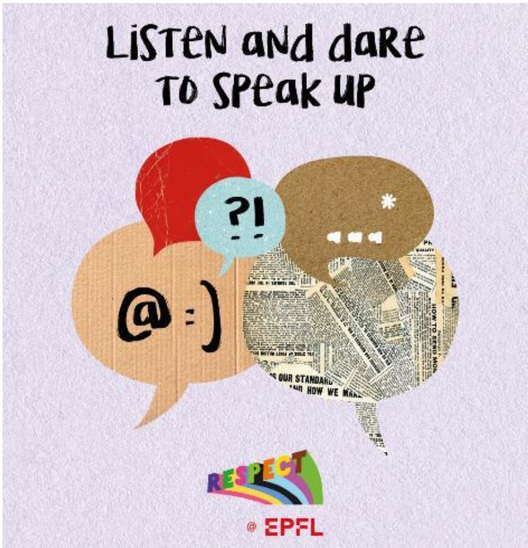
Your feedback is really important and will help improve the teaching and learning process at EPFL, so please take the time to give your honest and detailed opinion.

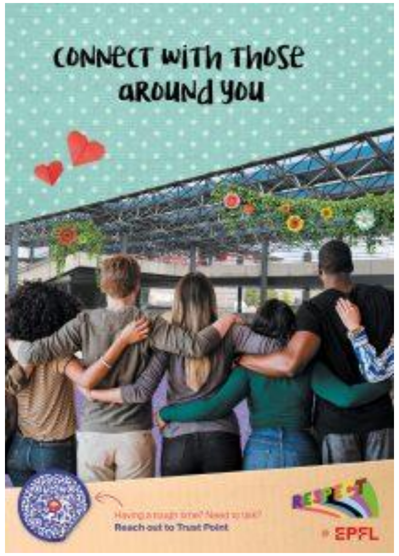
More info: https://www.epfl.ch/education/teaching/fr/soutien-a-lenseignement/ressources-etudiants/#indicativefeedback

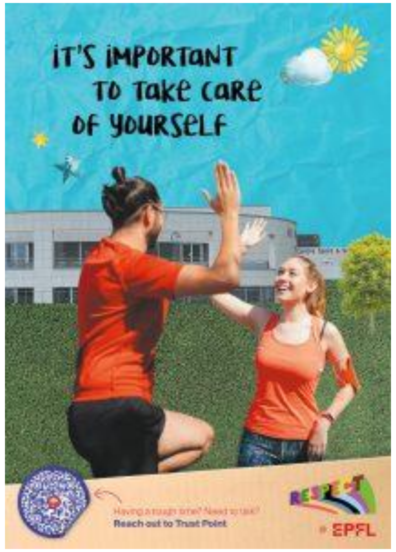
Questions?


RESPECT
respect.epfl.ch









https://www.epfl.ch/about/respect/the-respect-campaign/

https://www.epfl.ch/about/respect/the-respect-campaign/

Safe Space

https://go.epfl.ch/safespace

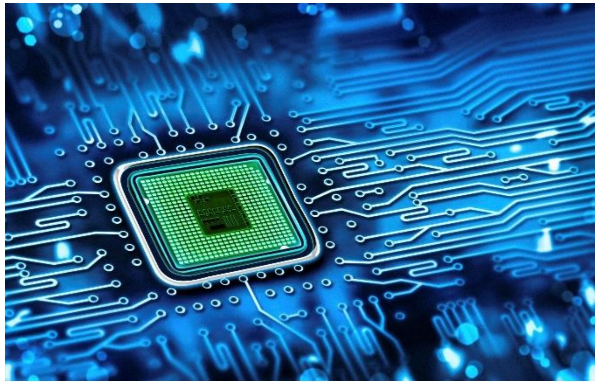
Course topics and books

- Generalities on semiconductors (bulk and nano)
- Semiconductor history and role of material science
- Chemical bonds and electronic band origin
- Crystal structure and energy bands
- Electrons, holes and effective masses
- Density of states, charge carriers, Fermi energy
- Doping in semiconductors
- Charge transport
- Optical properties
- Surfaces, interfaces and heterostructures
- Semiconductor devices
- Physics of nanostructures

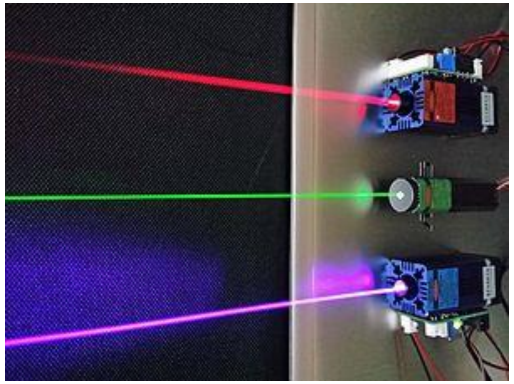
Bibliography:

- «The Physics of Semiconductors: An Introduction Including Nanophysics and Applications» by Marius Grundmann (Springer)
- "Electronic and optoelectronic properties of semiconductor structures" Jasprit Singh (Cambridge University Press)

Semiconductors in everyday life



Integrated circuits



Lasers

Energy conversion

Sensing (chemical, pressure, temperature, optical...)

Illumination

Screens

What is a semiconductor?

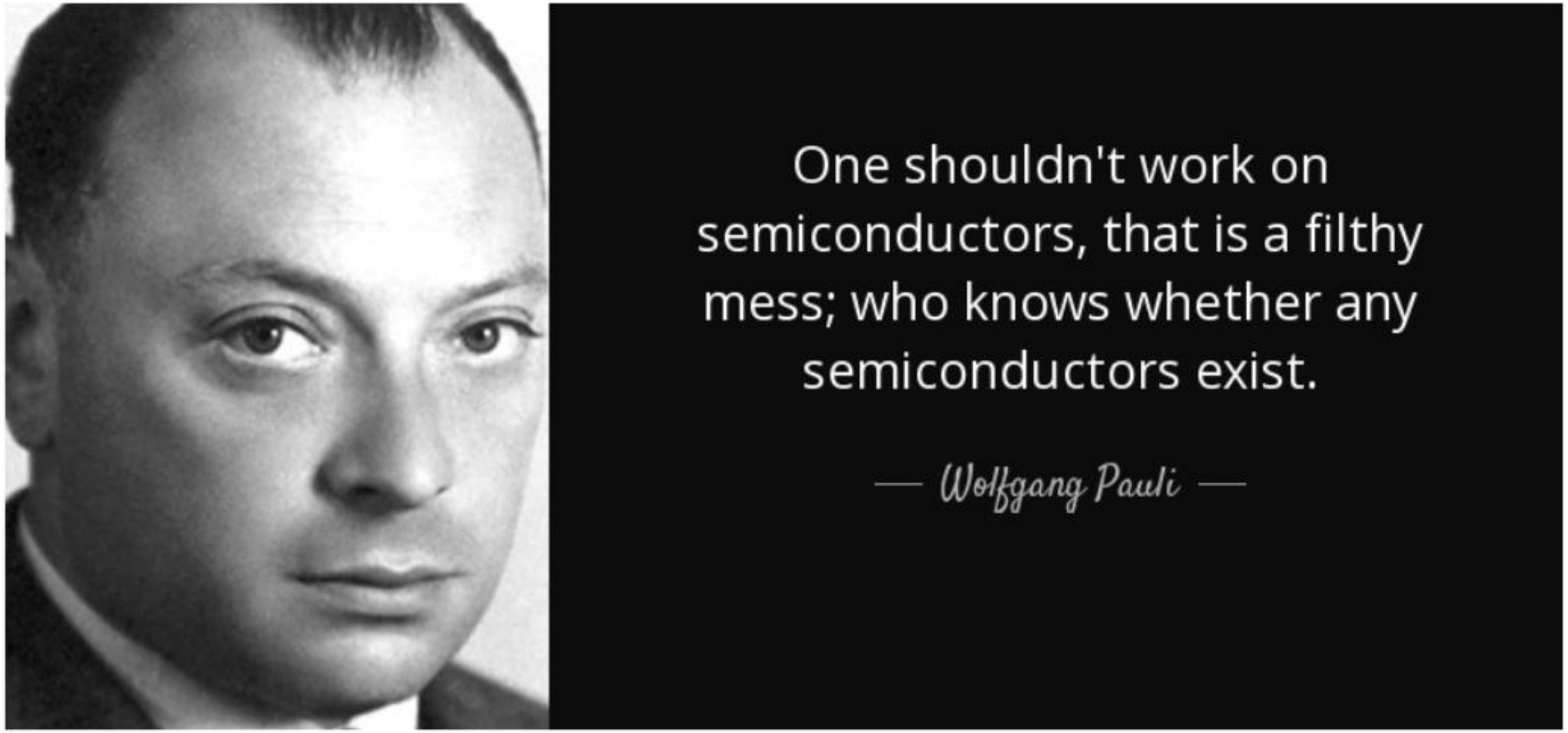
Which tangible properties characterize a «semi-conductor»?

Main milestones in semiconductor history

- **1821** T.J. Seebeck—discovery of thermopower (electrical phenomena upon temperature difference) in PbS, FeS2, CuFeS2
- **1873** W. Smith—discovery of photoconductivity in selenium
- **1874** F. Braun—discovery of rectification in metal–sulfide semiconductor contacts
- **1883 Ch. Fritts—first solar cell, based on an gold/selenium rectifier**
- **1907** H.J. Round—discovery of electroluminescence investigating yellow and blue light emission from SiC
- **1909** K. Bädeker—discovery of doping. Controlled variation of the conductivity of CuI by dipping into iodine solutions (e.g. in chloroform) of different concentrations
- **1911** The term ‘Halbleiter’ (semiconductor) is introduced for the first time by J.Weiss and J. Königsberger. Königsberger preferred the term ‘Variabler Leiter’ (variable conductor).
- **1925** J.E. Lilienfeld—proposal of the metal-semiconductor field-effect transistor (MESFET), with suggested copper sulfide thin film channel and aluminum gate
- **1928 F. Bloch—quantum mechanics of electrons in a crystal lattice, ‘Bloch functions’.**
  O.V. Losev—description of the light emitting diode (SiC)
- **1931** W. Heisenberg—theory of hole (‘Löcher’) states.
  R. de L. Kronig and W.G. Penney—properties of periodic potentials in solids.
  A.H. Wilson—development of band-structure theory

An «unbelievable» material

1931, W. Pauli, Letter to Peierls

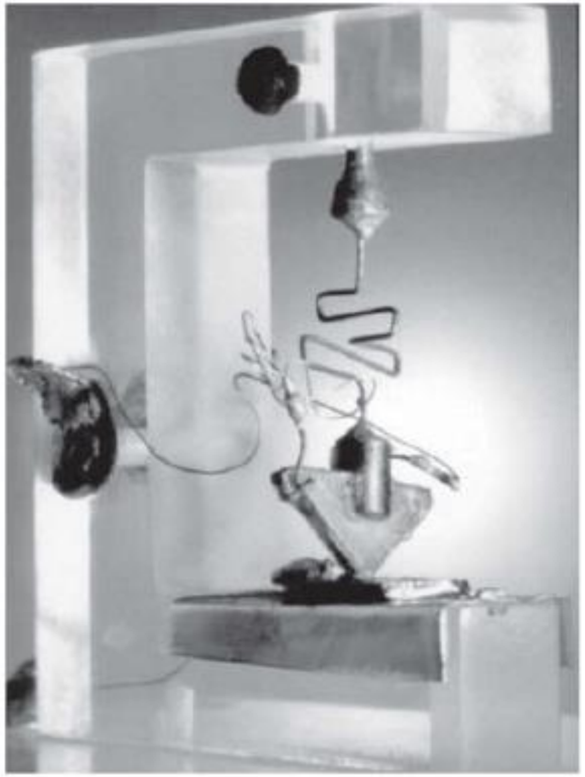


Nobel Prize Winner, 1945

For the theory on electron exclusion principle

Main milestones in semiconductor history

- **1938** **B. Davydov—theoretical prediction of rectification at pn-junction.**
  Schottky—theory of the boundary layer in metal–semiconductor contacts, being the basis for Schottky contacts and field-effect transistors.
- **1940** R.S. Ohl—Silicon-based photoeffect (solar cell) from a pn-junction
- **1947** **W. Shockley, J. Bardeen and W. Brattain fabricate the first transistor in the AT&T Bell Laboratories.**
- **1953** D.M. Chapin, C.S. Fuller and G.L. Pearson—invention of the silicon solar cell at Bell Laboratories.
- **1958** J.S. Kilby made the first integrated circuit at Texas Instruments.
- **1960** **R. Feynman, There is plenty of room at the bottom**
- **1962** The first semiconductor laser on GaAs basis at 77K at GE, IBM and MIT.
- ...
- ...
- **1992** S. Nakamura—growth of high-quality group-III–nitride thin films, blue nitride heterostructure LED with efficiency exceeding 10%
- **1997** First organic LED



First Transistor, 1947

Main milestones in semiconductor history

The Nobel Prize in Chemistry 2023

Ill. Niklas Elmehed © Nobel Prize Outreach

Moungi G. Bawendi

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Louis E. Brus

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Aleksey Yekimov

Prize share: 1/3

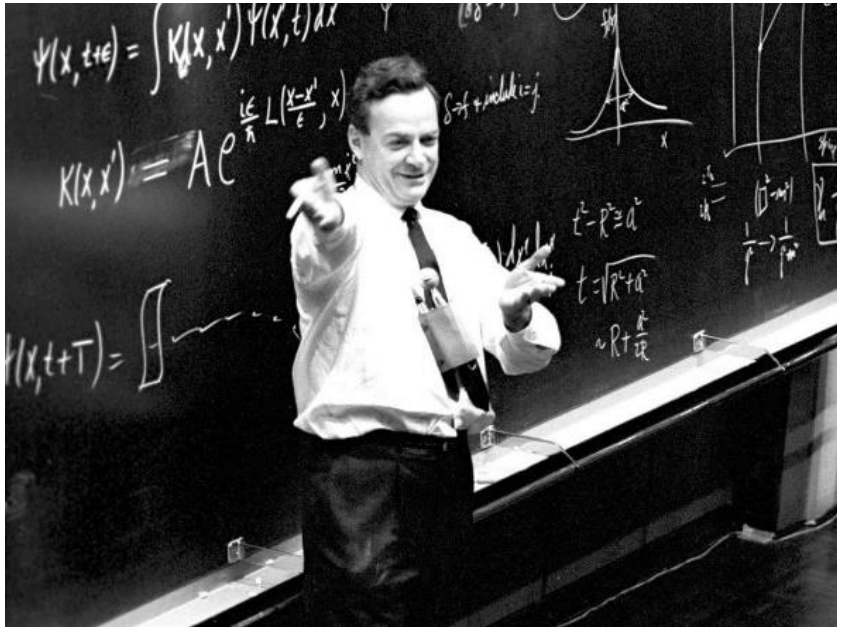
The Nobel Prize in Chemistry 2023 was awarded to Moungi G. Bawendi, Louis E. Brus and Aleksey Yekimov "for the discovery and synthesis of quantum dots"

More than 10 Nobel prize awards for semiconductor science and engineering (from 1909 to 2024)

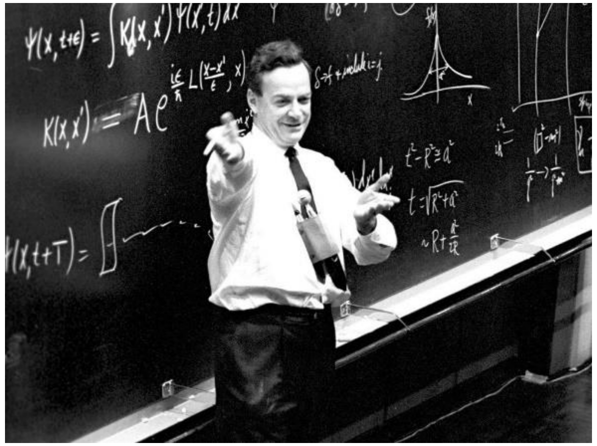
Plenty of Room at the Bottom

Richard Feynman, «There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics », 1960

"This field is not quite the same as the others in that it will not tell us much of fundamental physics (in the sense of, ``What are the strange particles?'') but it is more like **solid-state physics** in the sense that **it might tell us much of great interest about the strange phenomena that occur in complex situations.** Furthermore, a point that is most important is that it would have an enormous number of technical applications. "



Plenty of Room at the Bottom



"Why cannot we write the entire 24 volumes of the Encyclopedia Brittanica on the head of a pin?"

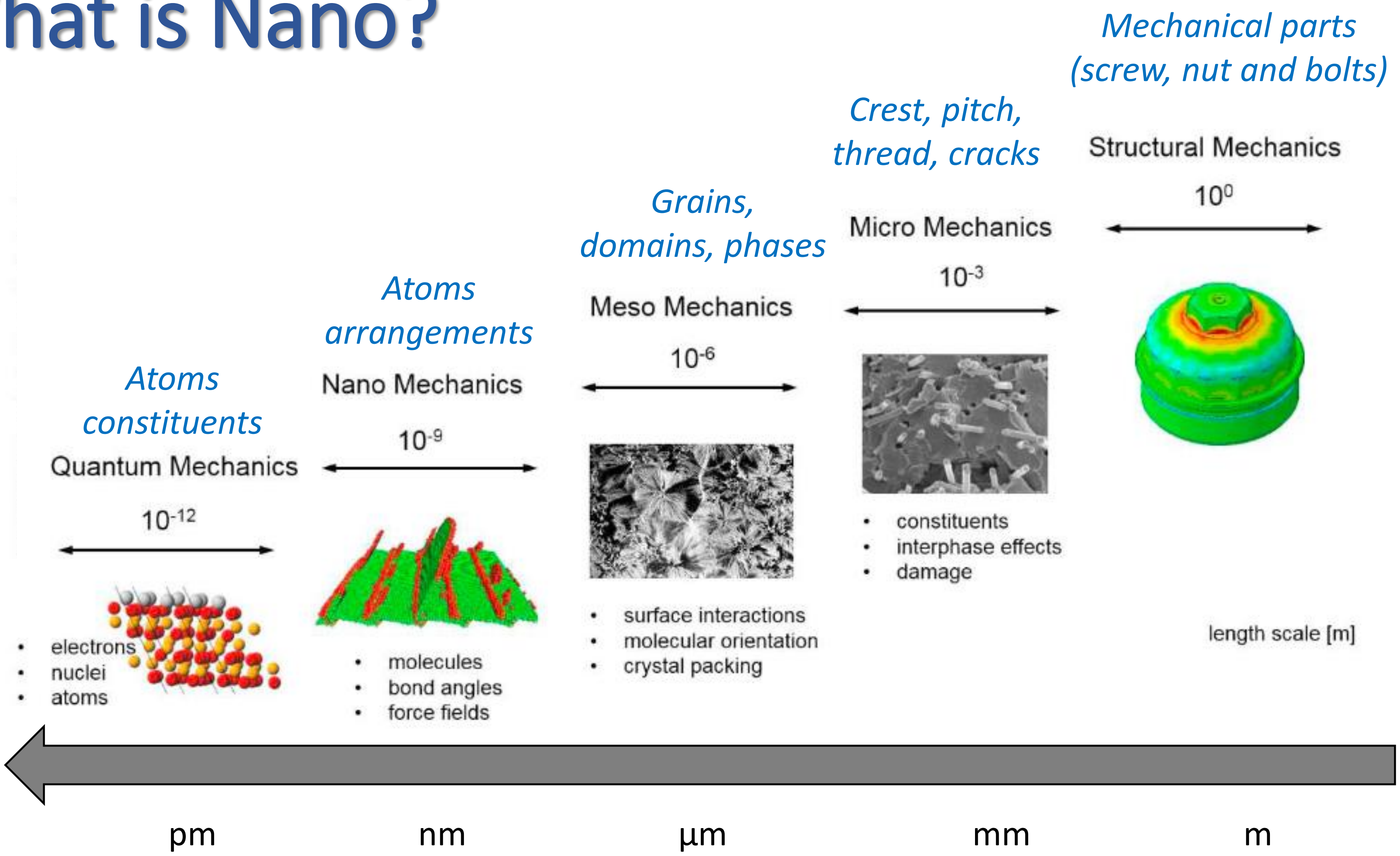
"[...] The head of a pin is a sixteenth of an inch across *(1.5 mm around)*. If you magnify it by **25,000 diameters**, the area of the head of the pin is then equal to the area of all the pages of the Encyclopaedia Brittanica. Therefore, all it is necessary to do is to reduce in size all the writing in the Encyclopaedia by 25,000 times. Is that possible?

The resolving power of the eye is about 1/120 of an inch (*0.2 mm*)---that is roughly the diameter of one of the little dots on the fine half-tone reproductions in the Encyclopaedia. This, when you demagnify it by 25,000 times, is still **80 angstroms in diameter---32 atoms across**, in an ordinary metal. In other words, **one of those dots still would contain in its area 1,000 atoms.**

So, each dot can easily be adjusted in size as required by the photoengraving, and there is no question that there is enough room on the head of a pin to put all of the Encyclopaedia Brittanica. "

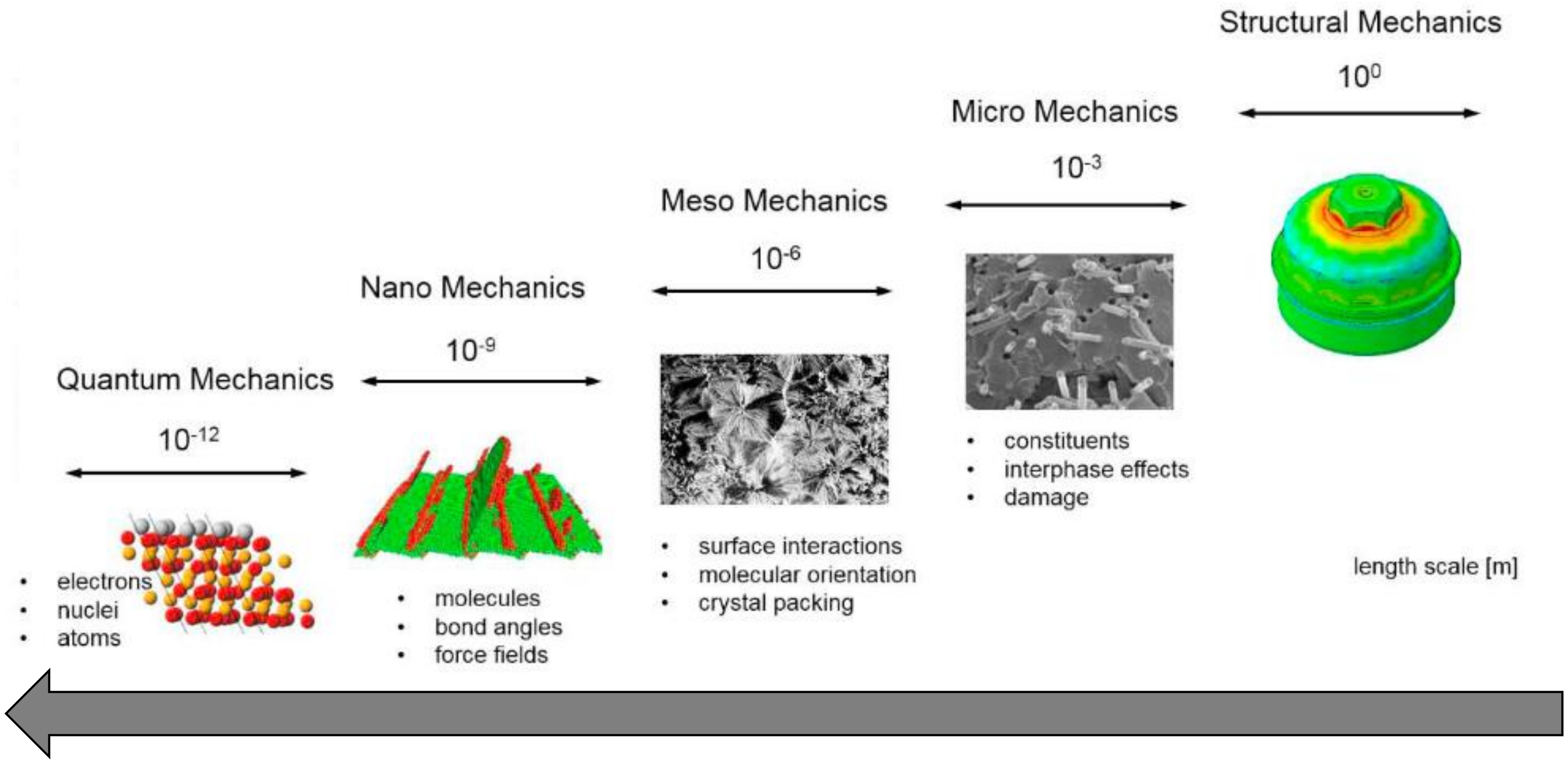
Nanotechnology
Nanoscience
Nanomaterials

What is Nano?



<u>*Michael Hack et al., Procedia Engineering 213 (2018)*</u>

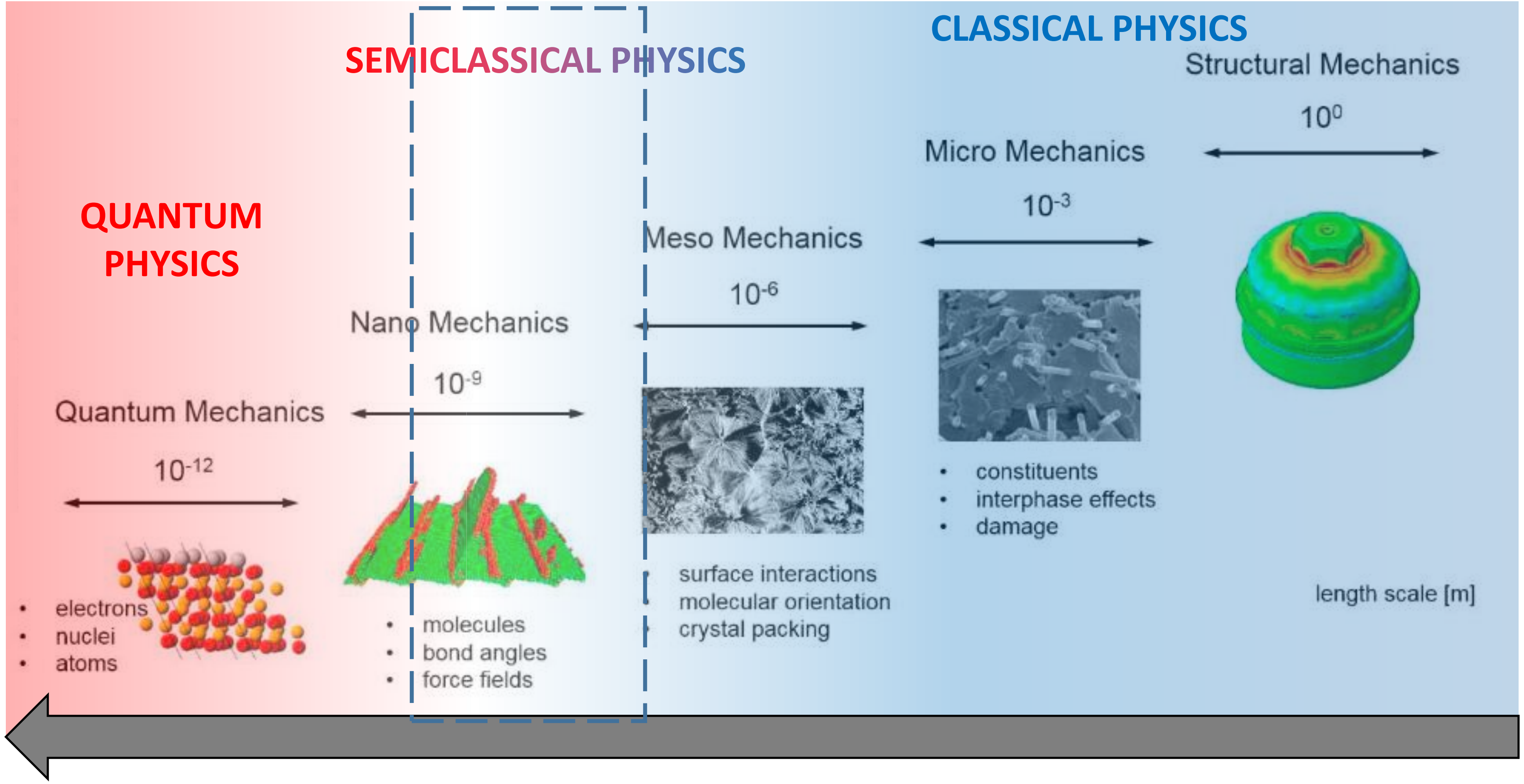
Number of Atoms



pm ~ 1 Atoms nm ~ 1000 Atoms µm ~ 10^{6} Atoms mm ~ 10^{9} Atoms m

Michael Hack et al., Procedia Engineering 213 (2018)

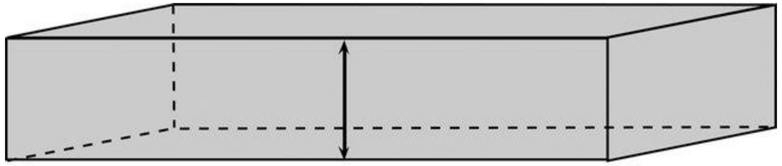
Physical Models



pm ~ 1 Atoms nm ~ 1000 Atoms µm ~ 10^6 Atoms mm ~ 10^9 Atoms m

Michael Hack et al., Procedia Engineering 213 (2018)

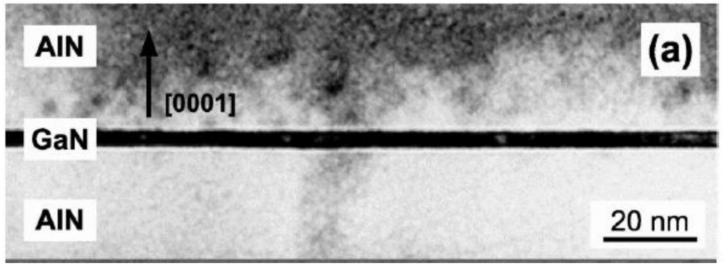
Dimensionalities

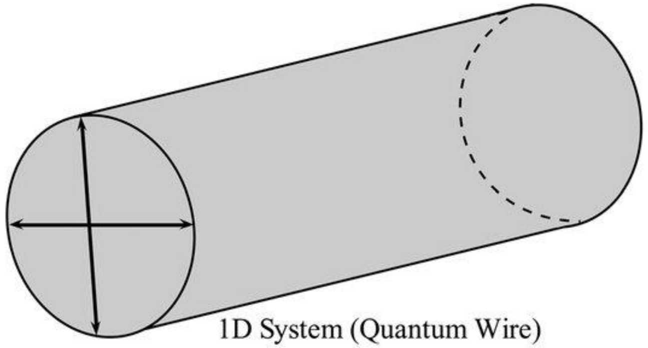


2D System (Quantum Well)

2 macroscopic dimensions

TEM IMAGE of GaN QW in AlN

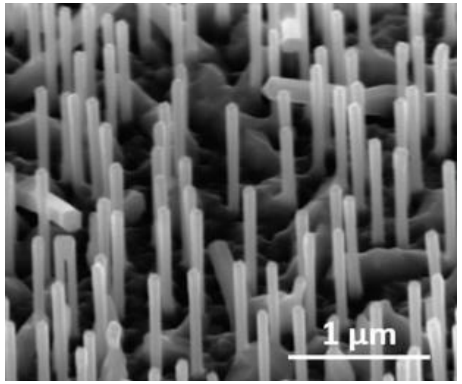


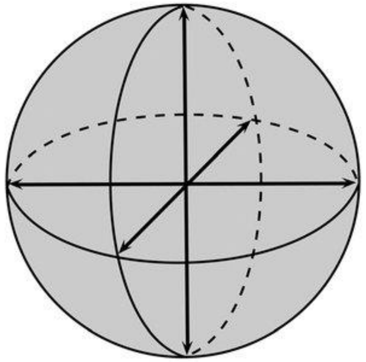


1D System (Quantum Wire)

1 macroscopic dimension

SEM IMAGE of GaAs NWs

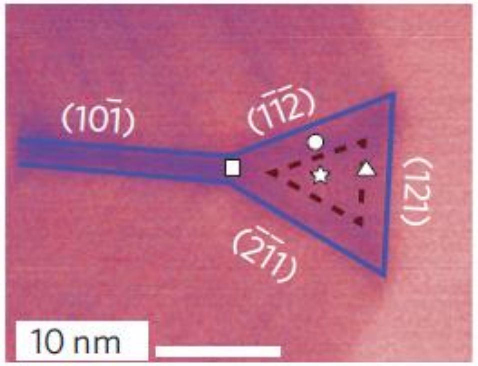




0D System (Quantum Dot)

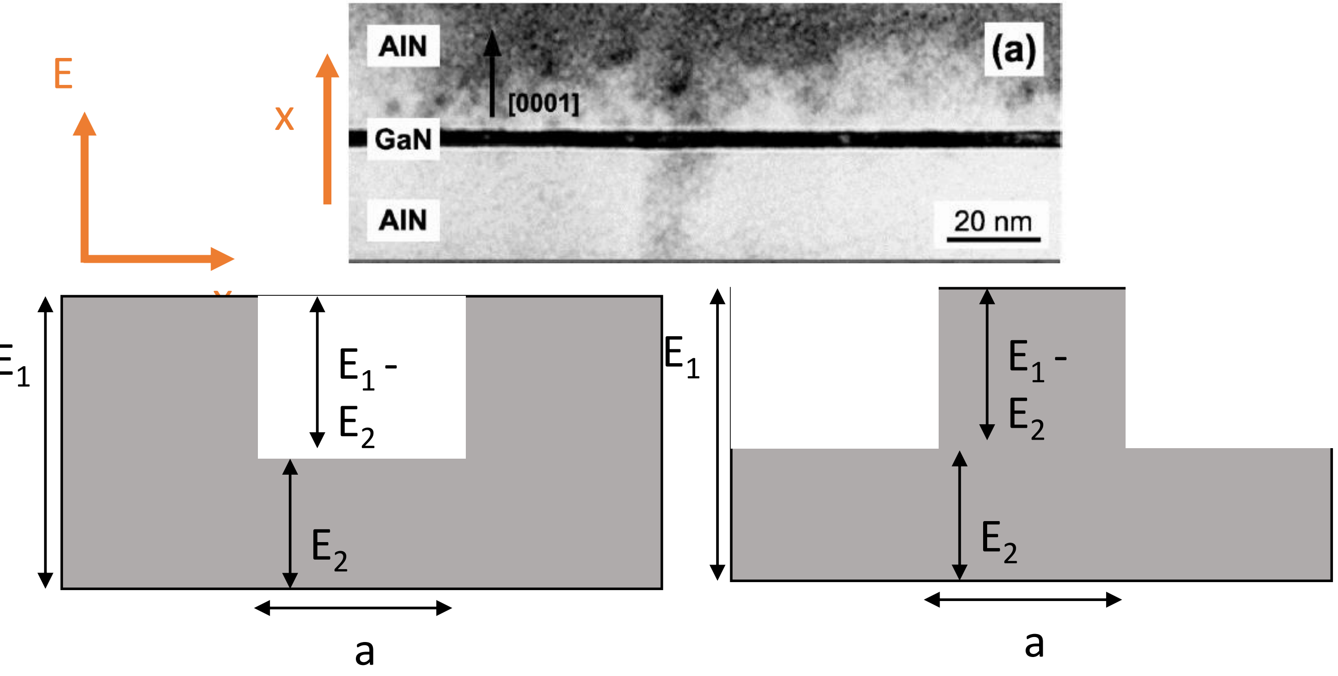
0 macroscopic dimension

STEM IMAGE of an AlGaAs QD



Quasi-2Ds and 2Ds

Quasi 2D Material: Quantum Well and Quantum barrier



Quasi 2D Materials: Systems engineered to have an energy difference in a nanometric portion of material («*a*»)

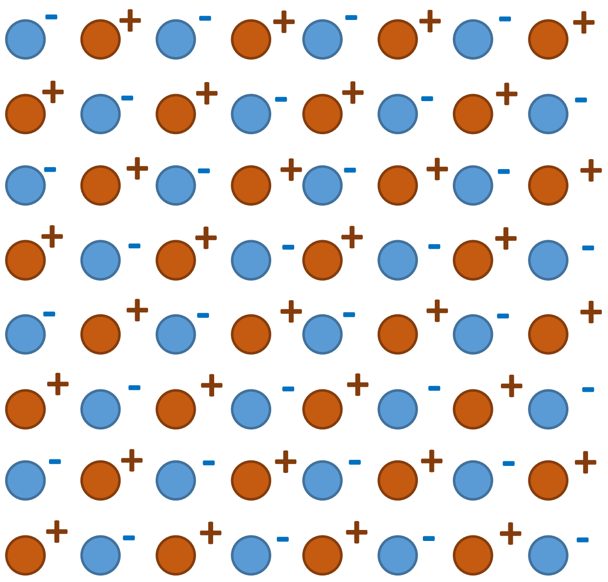
2D Materials (VdW materials)

2D Materials: layered materials with strong in-plane bonds and weak, van der Waals-like coupling between layers.

In 2D crystals, the unit cell repeats itself only in two directions.

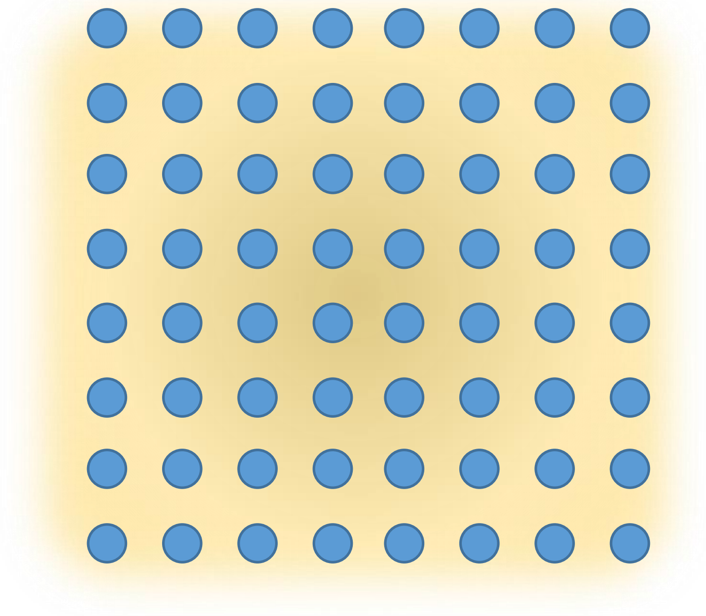
Types of bonds

IONIC BOND



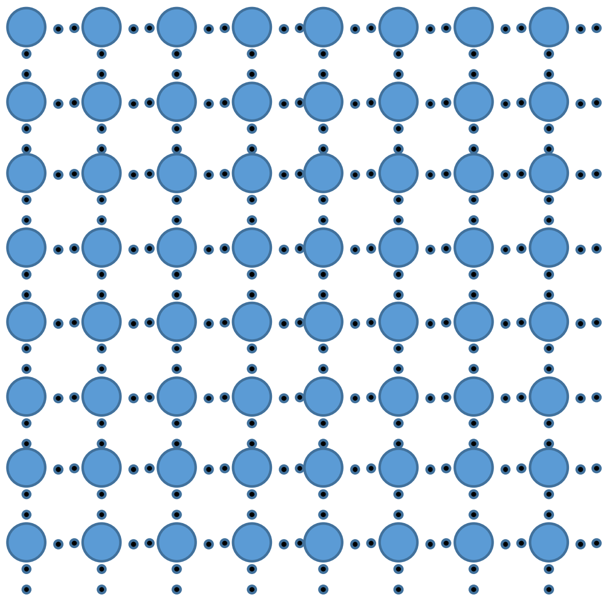
Charges belong to a single nucleus

METALLIC BOND



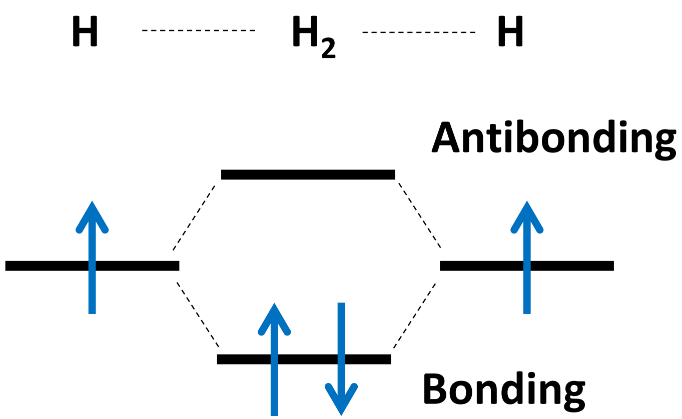
Charges belong to all the nuclei

COVALENT BOND

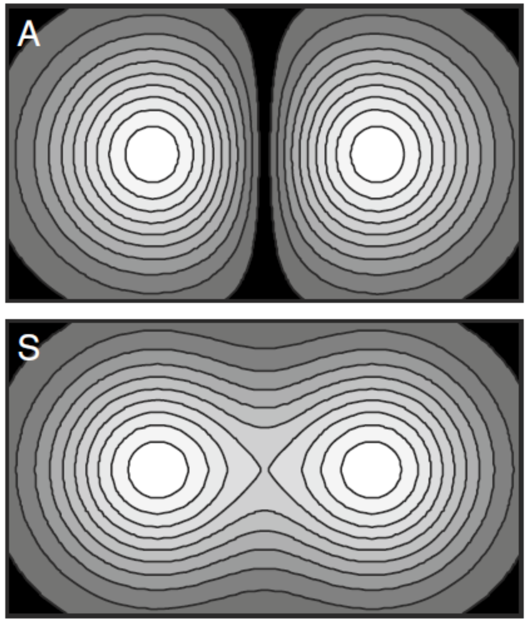


Charges belong to some nuclei (non-trivial many body problem)

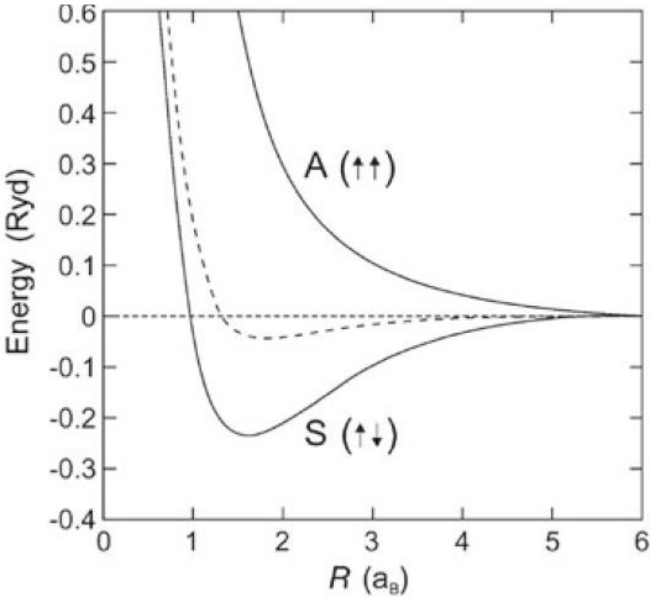
Bohr model for H_2



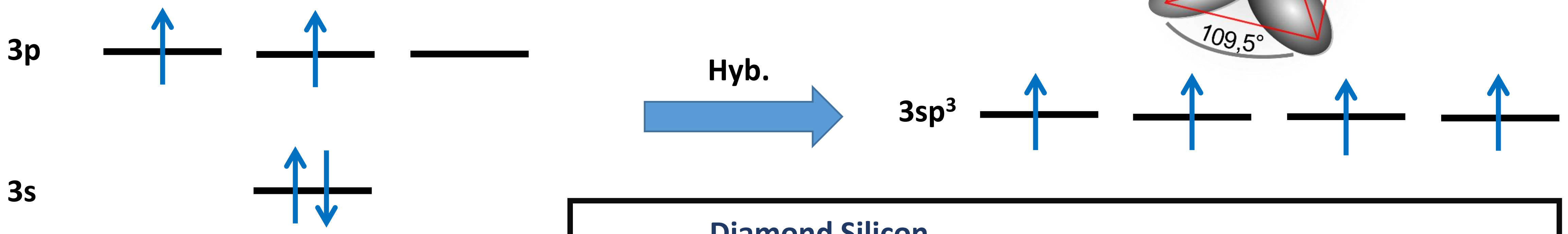
$$\Psi(\mathbf{r}) * \Psi(\mathbf{r})$$

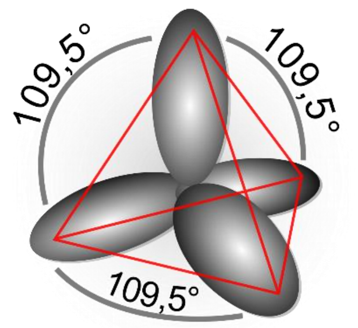


$$H\,\Psi(\mathbf{r}) = \left[-\frac{\hbar^2}{2m}\nabla^2 + U(\mathbf{r})\right]\Psi(\mathbf{r}) = E\,\Psi(\mathbf{r})$$



Diamond Si





Diamond-structure

Diamond Silicon