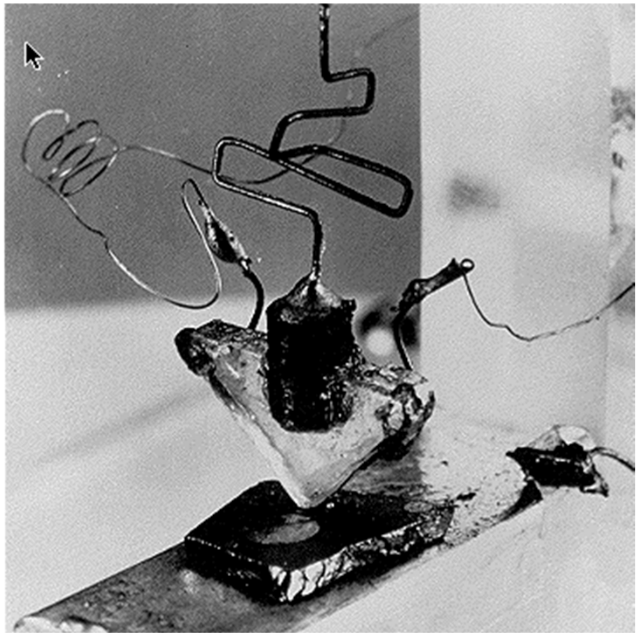
Semiconductor physics and light-matter interaction

Lectures: Dr. Raphaël Butté (MER-senior scientist)
Teaching assistant: Samuele Brunetta

Physics - Master, fall semester 2024



Who are we?

Raphaël Butté (Lectures)

- PhD in Physics, Univ. Lyon, France, 2000
- Postdoctoral research associate, Univ. Sheffield, UK, 2000-2003
- Senior scientist (MER) at LASPE (https://laspe.epfl.ch/), EPFL, 2004-

Research interests: III-V semiconductors (III-N, III-As), quantum nanostructures, optoelectronic properties, nanophotonics: waveguides and microring resonators (nonlinear optics) & microcavities and photonic crystals (light-matter interaction), LEDs, laser diodes and nanolasers, single photon emitters

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Samuele Brunetta (Exercises)

- MSc. in Physics, University of Padua, Italy, 2022
- PhD in Physics at LASPE, EPFL, 2022-

Research interests: III-V semiconductors, nonlinear optics, nanofabrication, nanophotonics

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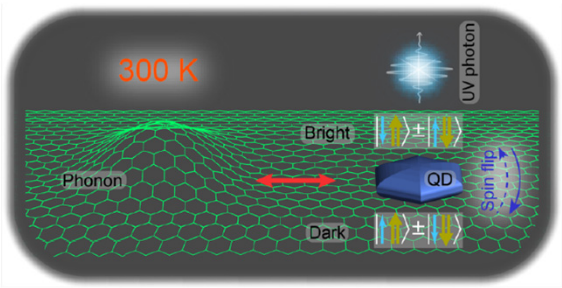
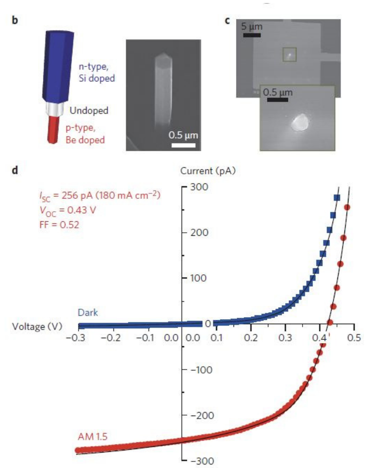
Semiconductors at EPFL

Inorganic semiconductors

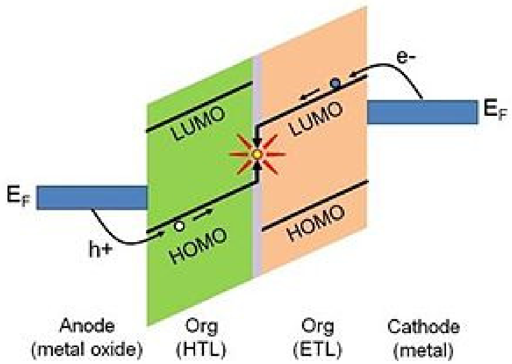
- SB / IPHYS → LASPE (III-N)
- SB / IPHYS → GR-GA (diamond)
- STI → LMSC (III-V)
- STI → PV-LAB (Si)
- STI → LANES (MoS_2)
- STI → Powerlab (III-N)



Bright room temperature single photon emission GaN quantum dots
ACS Phot. **7**, 1515 (2020)
Light: Sci. & Appl. **11**, 114 (2022)



p-i-n junction GaAs nanowire solar cells
Nat. Phot. **7**, 306 (2013)



OLEDs

An emblematic example: the smart phone

Information technology perspective

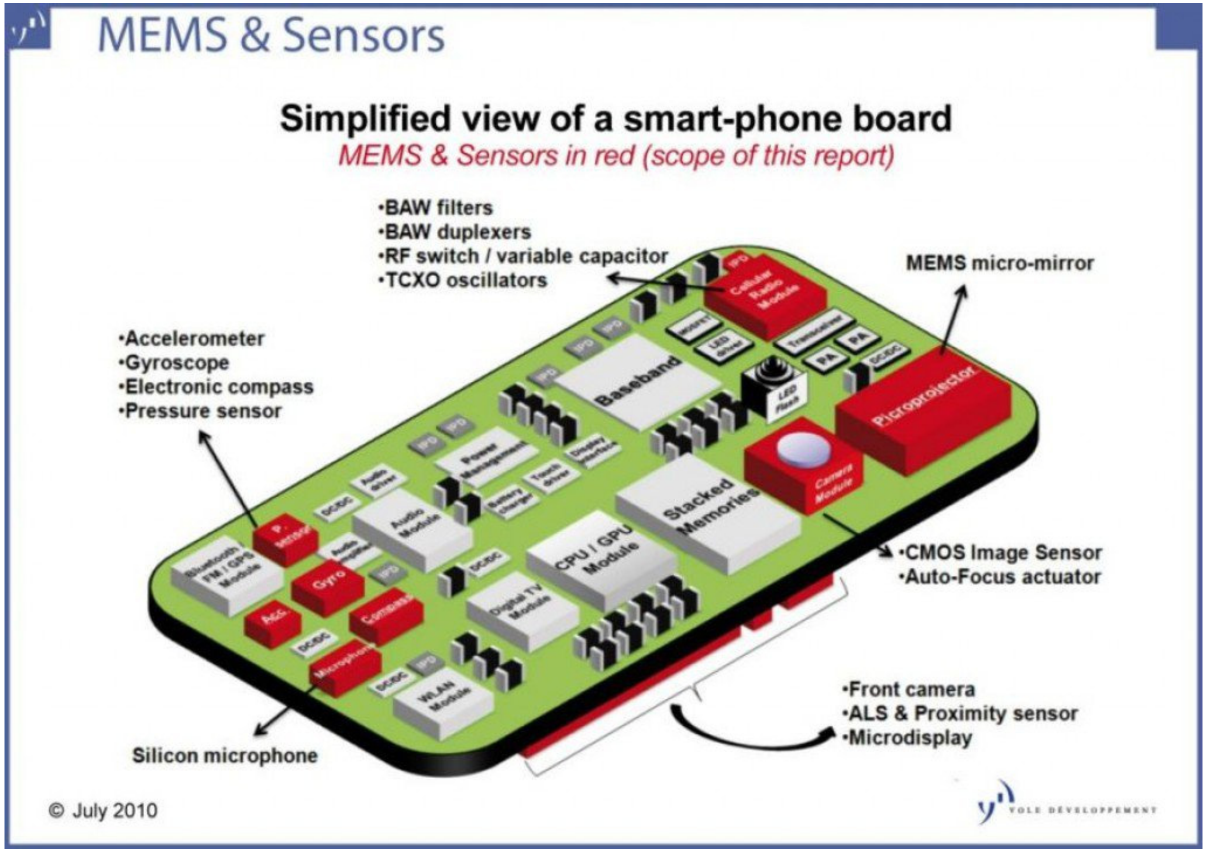
JPEG

WiFi

MP3

An emblematic example: the smart phone

Semiconductor perspective



An emblematic example: the smart phone

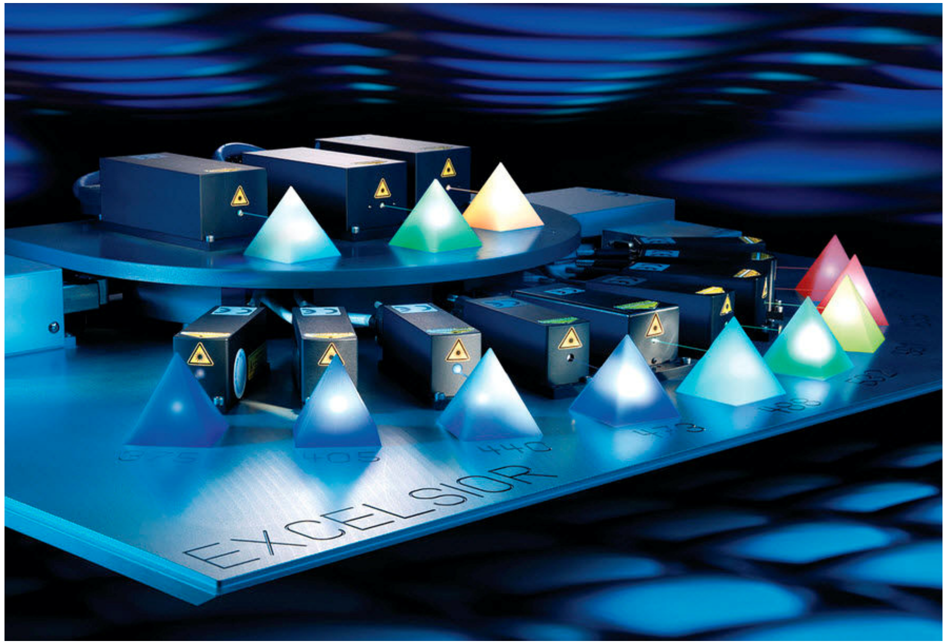
- *The chips in a typical smartphone must send and receive signals for voice calls, Wi-Fi, Bluetooth and the Global Positioning System, while also sensing touch, proximity, acceleration, magnetic fields — even fingerprints. On top of that, the device must host special-purpose circuits for power management, to keep all those functions from draining the battery.*

- *“Different components, **different materials, electronics, photonics** and so on, all in the same package — these are issues that will have to be solved by new architectures, new simulations, new switches and more.”*

M. M. Waldrop, Nature **530**, 144 (2016)

The laser diode

An essential building block of the Internet and information technology (IT)



Coherent light emission?

Stimulated emission?

Efficiency (WPE)?

Operating wavelength?

Effect of temperature?

Lifetime?

Cost?

Objectives of the fall and spring semesters

Semiconductors are a unique class of materials in that they form a versatile family bridging fundamental physical concepts at play in condensed matter and real world applications

- ***Understand***
  - ✓ What are the physical properties of semiconductors?
  - ✓ Where do they come from?
  - ✓ How can we play with them?

- ***Describe*** and ***explain*** semiconductor/device properties (*p-n* junction, light-matter interaction, optical gain, quantum heterostructures, single photon emitters, LEDs vs. LDs)

- ***Know*** the main application fields of optoelectronic devices

- ***Choose*** the right optoelectronic device for a given application

- ***Be prepared*** for academic research and/or R&D

Philosophy of the lectures and the exercises

- **Lectures** essentially **based on the books "Physics of Semiconductor Devices"** by S. M. Sze (John Wiley and Sons, New York, 1981 and subsequent editions) and **"Optoelectronics"** by E. Rosencher and B. Vinter (Cambridge University Press, Cambridge, 2002), paperback books available at the central library (+ eBook)

- **Master lectures** are a **transition between propaedeutic years and the world of work**: no dedicated lecture notes as teaching support, relevant and complementary information to be accessed mostly via textbooks and sometimes articles

- **Each week, a designated speaker** will present at the beginning of the lecture a **summary of the previous lecture** (maximum of two slides, to be sent the day before (deadline 2 pm) at raphael.butte@epfl.ch) focusing on the main points to know $\Rightarrow$ to be validated during the lecture $\equiv$ **useful memo!**

Aim: improve (i) your **ability to extract essential concepts** and (ii) your **presentation skills** on scientific/technical concepts in front of a medium size audience

Recommended textbooks

- **S. M. Sze “*Physics of semiconductor devices*” (John Wiley & Sons, New York, 1981)**
  https://onlinelibrary.wiley.com/doi/book/10.1002/0470068329

- N. W. Ashcroft & N. D. Mermin, “*Solid state physics*” (Saunders College Publishing, Orlando, 1976)

- P. Y. Yu & M. Cardona, “*Fundamentals of semiconductors*”, 2nd edition (Springer-Verlag, Berlin, 1999) https://link.springer.com/book/10.1007%2F978-3-642-00710-1

- **E. Rosencher & B. Vinter, “*Optoelectronics*” (Cambridge University Press, Cambridge, 2002)**
  https://www.cambridge.org/core/books/optoelectronics/86B6621671230A798D5BFBE24266EE3F

Philosophy of the lectures and the exercises

- **Exercises supervised by Samuele Brunetta. Each week part of the exercises** will be done in the classroom while the other part should be **solved at home**. **Exercises are compulsory and will count for the final mark (1 pt out of 6).** Solutions to be uploaded on Moodle the week after. The corrections will be made available two weeks after the series. **Possibility of collective work but individual copies should be uploaded** (the individual character of each copy should be obvious to the reader).

Aim: focus on important/essential physical concepts described in the lectures, **handle mathematical tools**, work on concrete examples, **develop your ability to handle back-of-the-envelope calculations**

- **Written examination: 3 hours, full access to the content of the lectures + related notes and the exercises** (no book, etc.). **Format of the exam: ~ 2/3 on problem solving and ~ 1/3 on analysis of figures** (implying the detailed description of physical phenomena)

Downloading lectures + exercises

https://moodle.epfl.ch/course/view.php?id=14314

- Access to the pdf files of past lectures + pdf files of exercises
- Use of **Ed Discussion** via Moodle as a forum tool to manage questions related to the lectures and the exercises

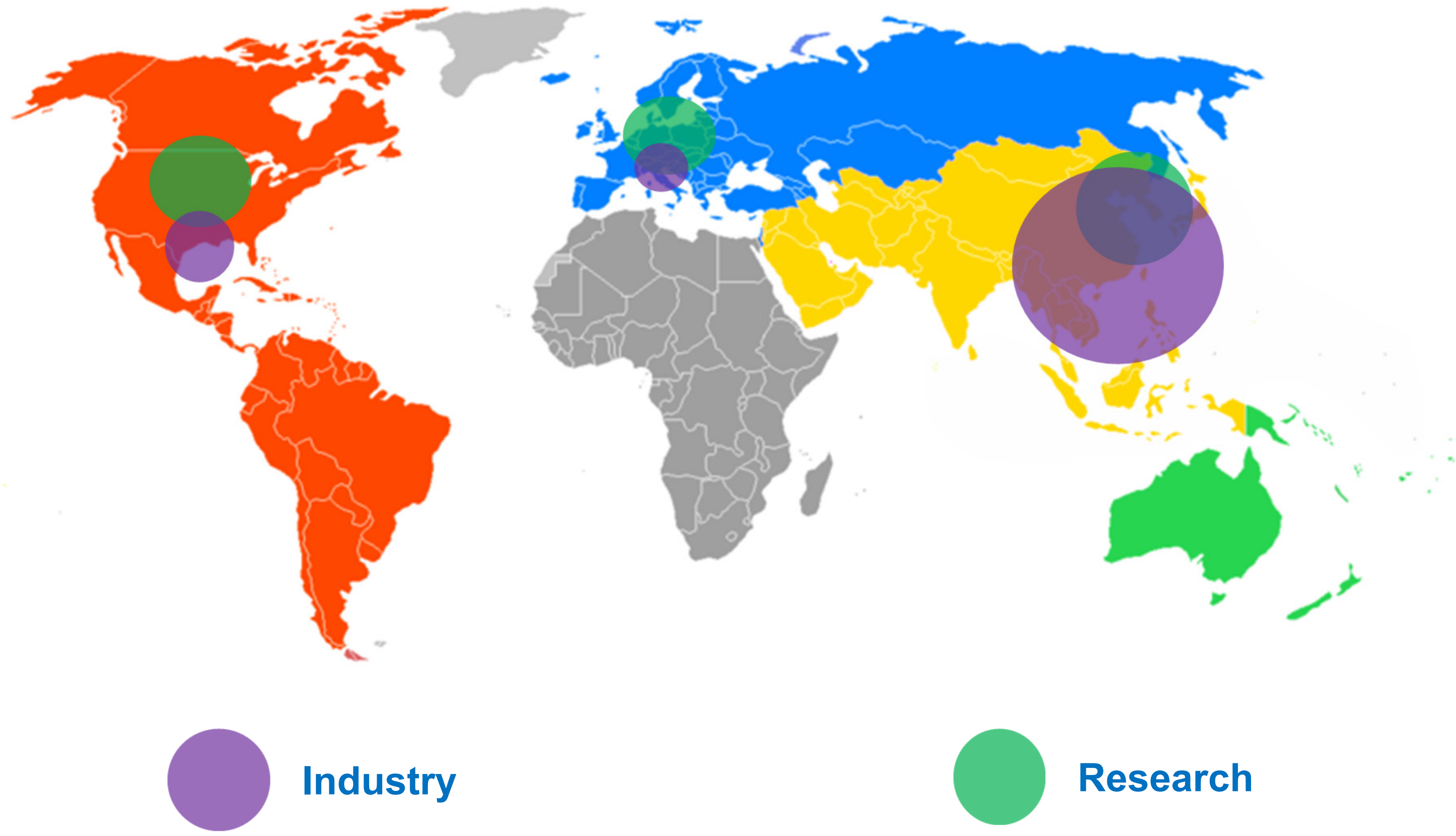
Content of the fall semester

1. **Electronic properties of semiconductors**
    a. Crystal structure and energy band diagrams
    b. Impurities and doping
    c. Carrier statistics in equilibrium and out-of-equilibrium
    d. Electron transport in weak and strong electric fields
    e. Generation and recombination processes

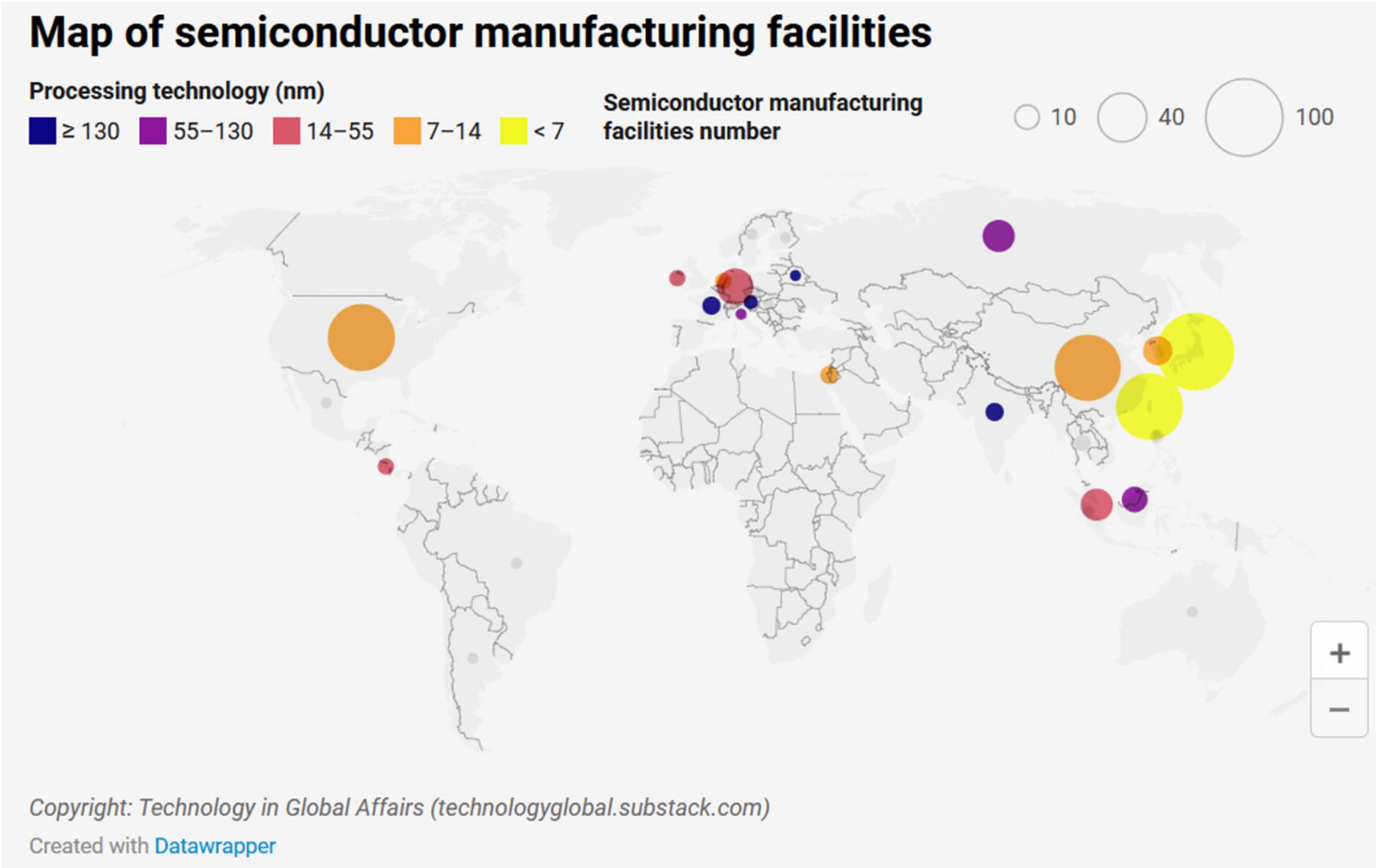
2. **Theory of junctions and interfaces**
    a. p-n and metal-semiconductor junctions
    b. Heterojunction interfaces

3. **Light-matter interaction in semiconductors**
    a. Fermi's golden rule, absorption, optical susceptibility, Bernard-Duraffourg condition
    b. Dielectric function, optical constants
    c. Spontaneous and stimulated emission of photons
    d. Radiative lifetime, reflectivity and photoluminescence spectra

Semiconductor research & industry



Semiconductor research & industry



https://technologyglobal.substack.com/p/semiconductor-manufacturing-facilities

Research & industry in Europe

Research:

- Germany
- UK
- France
- Netherlands
- Italy
- Switzerland (ETHZ, EPFL, CSEM, Basel, IBM)

2016 ITA Semiconductors and Semiconductor Manufacturing Equipment Top Markets Report

Semiconductors

According to World Semiconductor Trade Statistics (WSTS), the Europe/Middle East (ME) market for semiconductors was $34.3 billion in 2015, comprising 10.2 percent of the total worldwide market. ITA estimates based on semiconductor imports, production of electronic equipment containing semiconductors, and regional semiconductor market data placed the EU market at just under $30 billion, around 8.5 percent of the world market. Switzerland, Ukraine, Russia and Turkey are the only notable markets outside of the EU in this regional category, and no non-EU Member State market in the regional category is among ITA's top 20 U.S. export markets for semiconductors.

Industry:

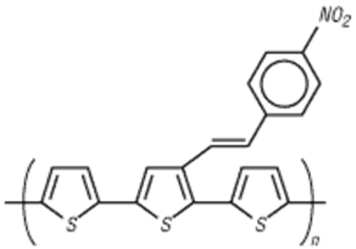
- STMicroelectronics
- Philips
- ASML
- AMS-Osram
- UMS
- Trumpf
- Thales
- LFoundry
- Soitec
- ABB, II-VI Incorporated, EM Microelectronic, Melexis, Exalos, Alpes Lasers

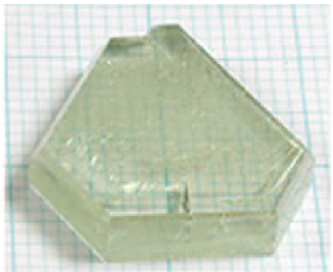
What is a semiconductor?

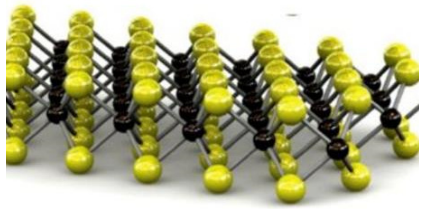
Organic molecules

Diamond

Silicon



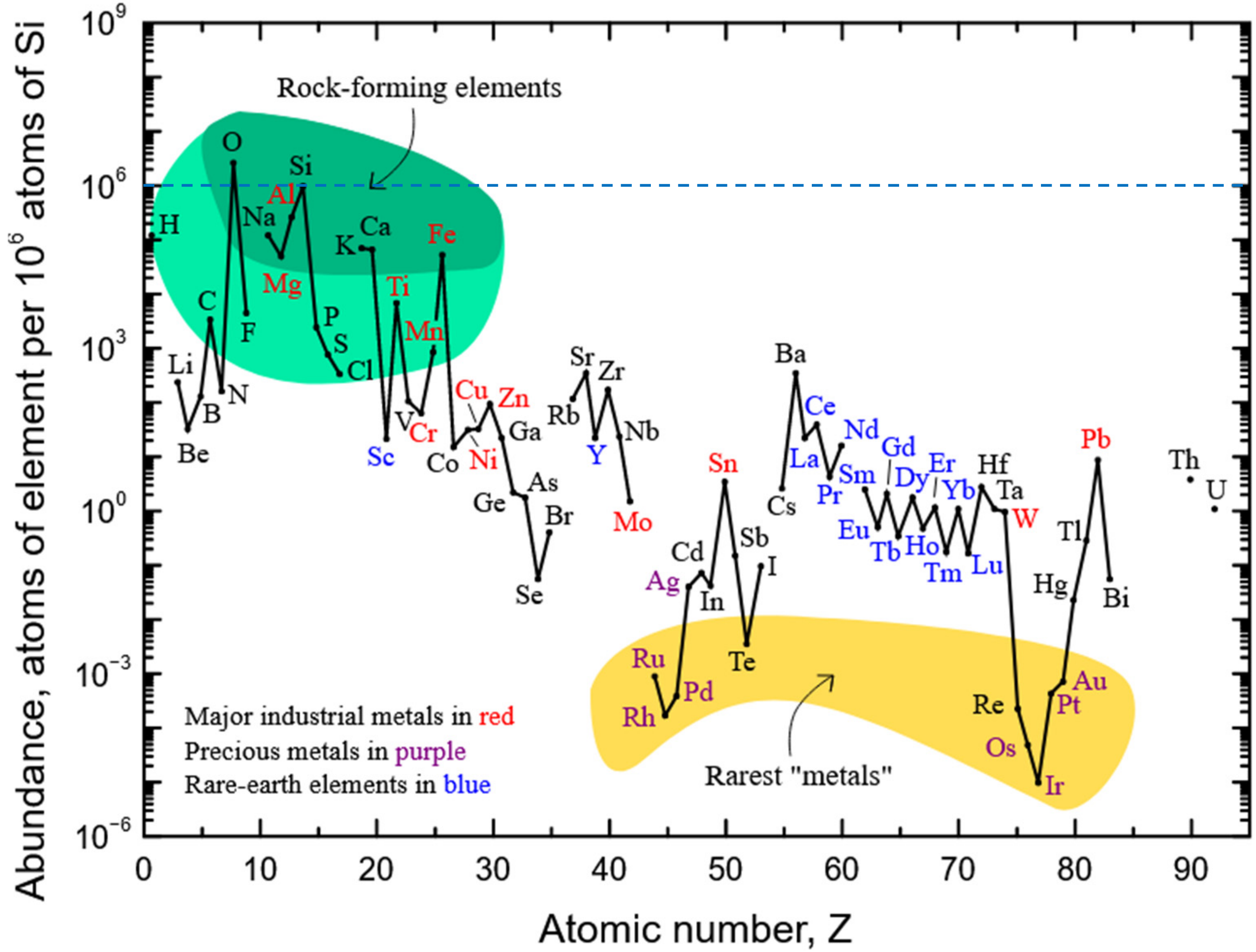




ZnO

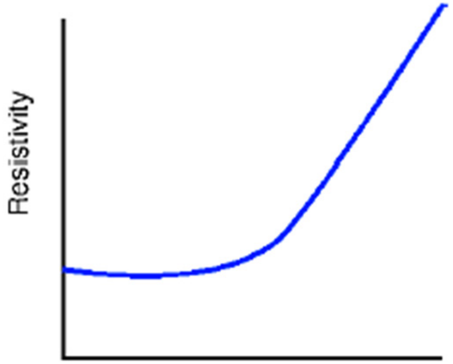
MoS_2

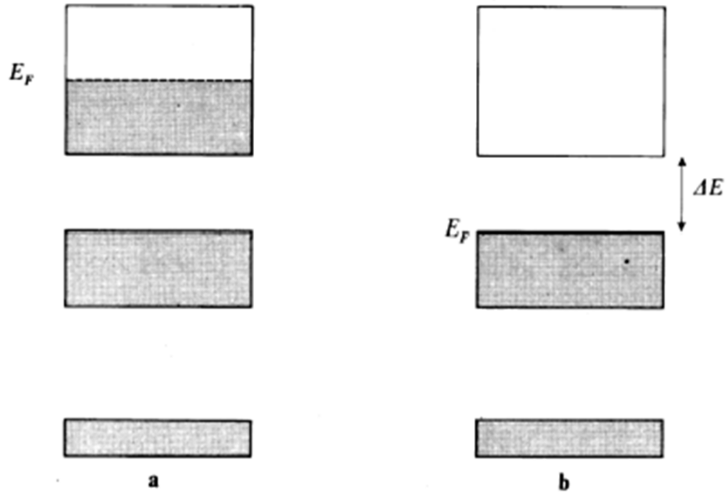
Abundance of the elements: what about semiconductors?



Metal vs. insulator

T = 0 K





metal insulator

Metal: the resistivity increases with the temperature

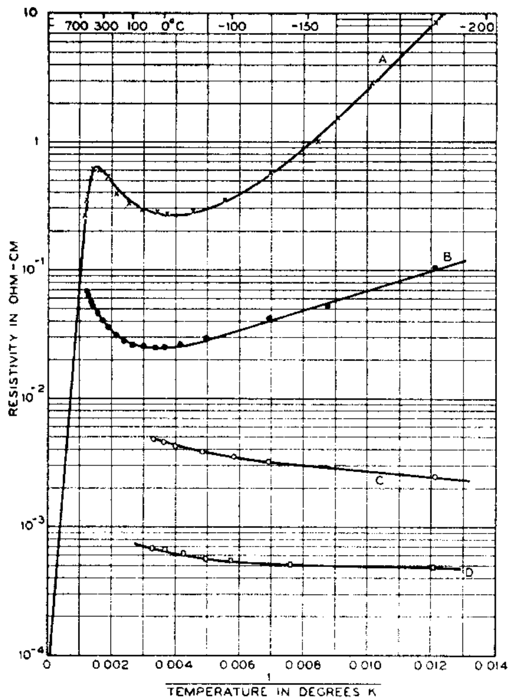
Semiconductor resistivity

TABLE 27.1 Resistivities and Temperature Coefficients of Resistivity for Various Materials

Material	Resistivity[a] ($\Omega \cdot m$)	Temperature Coefficient $\alpha[(°C)^{-1}]$
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[b]	1.50×10^{-6}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon	640	-75×10^{-3}
Glass	10^{10} to 10^{14}	
Hard rubber	$\approx 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

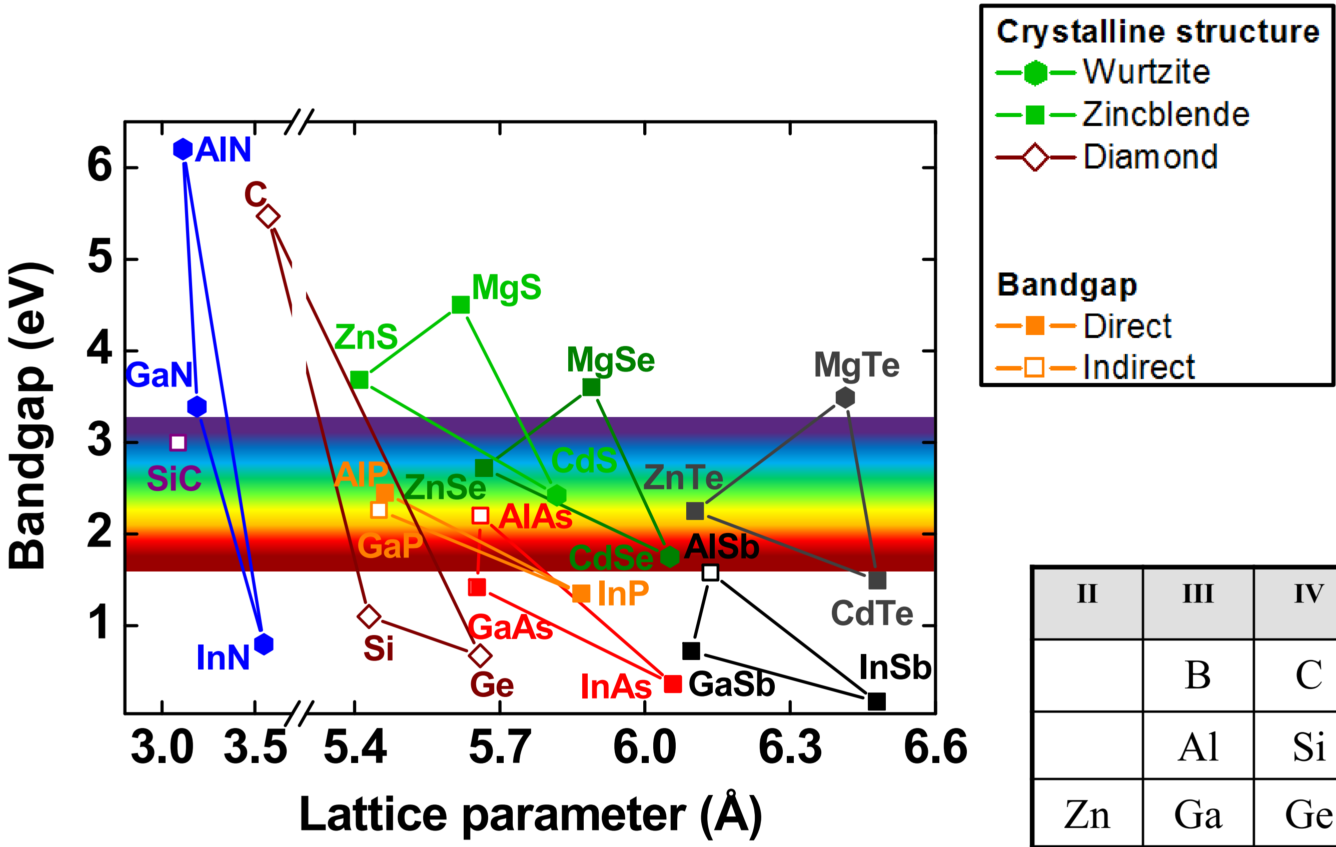
[a] All values at 20°C.

[b] A nickel–chromium alloy commonly used in heating elements.



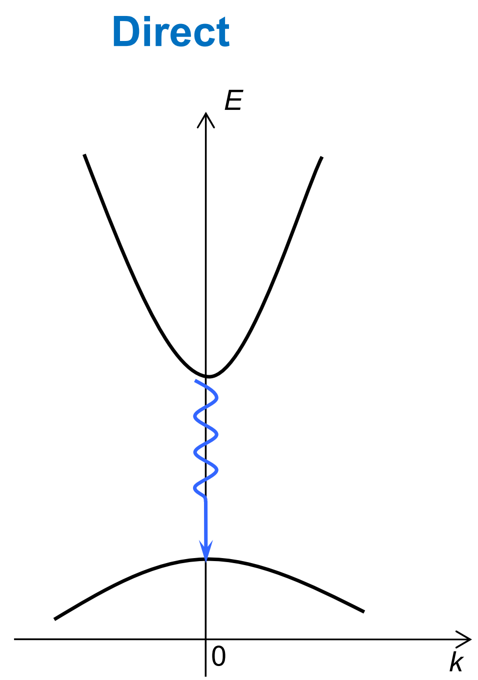
The resistivity decreases with increasing temperature

Bandgap and materials

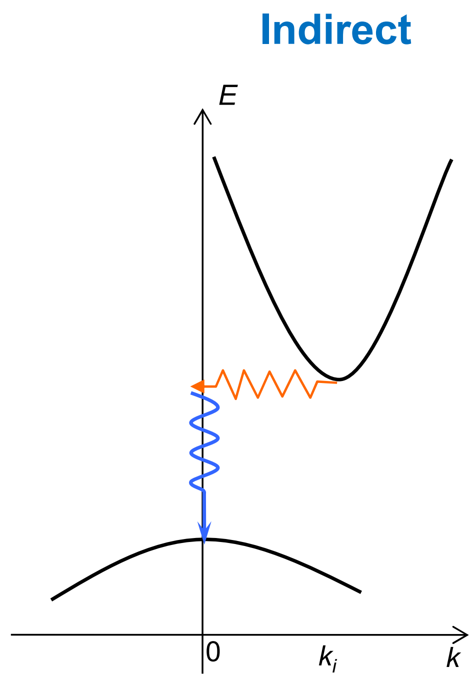


II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

Bandgap: direct or indirect



Optoelectronics



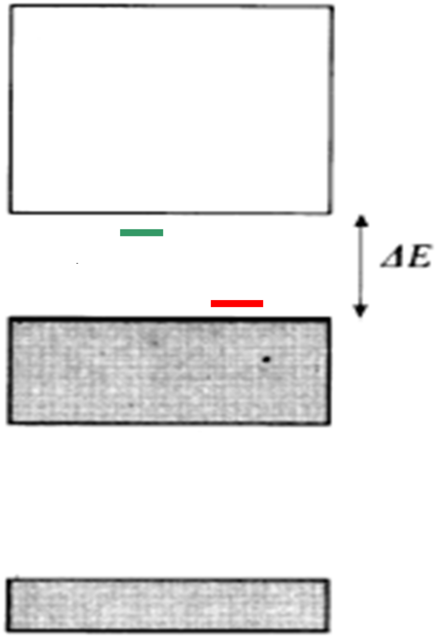
Electronics

Impurities in semiconductors

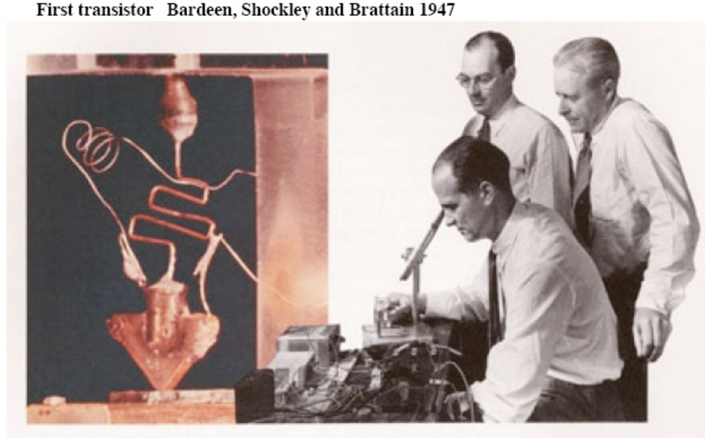
Donors and/or **acceptors** deeply modify the conductivity

At the origin of the *p-n* junction and the first transistor

(1947, Nobel prize in Physics 1956)



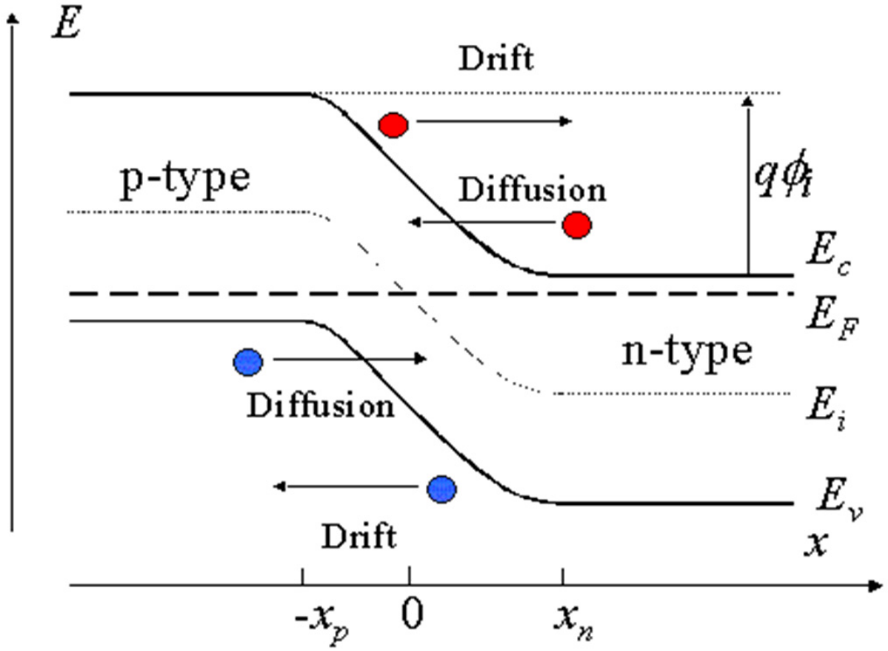
First transistor Bardeen, Shockley and Brattain 1947



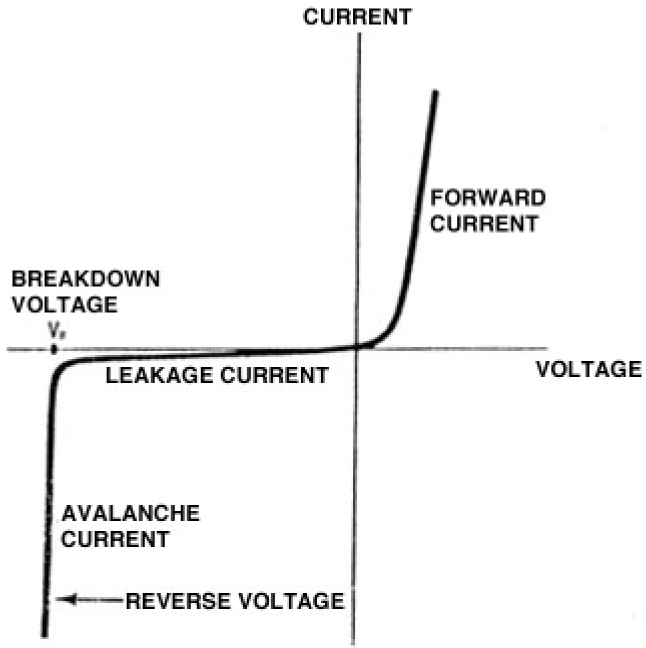
1939

AT&T Bell Laboratories

The *p-n* junction



I-V characteristic of a diode



Rectifying behavior

Relevant parameters for designing a useful device

- **Bandgap (electronic properties)**
- **Control of the conductivity (*p-n* junction)**
- **Quantum engineering (quantum wells, etc.)**
- **Photonic engineering (cavities, waveguides, etc.)**
- **Fabrication**
  - ✓ Performance
  - ✓ Cost
  - ✓ Lifetime (reliability)

Which device for which application?

- **Electronics:** only electrons (and/or holes)
  - Diodes and transistors

- **Optoelectronics:** electrons and/or holes and photons (emission or absorption)
  - Emitters: LEDs, LDs, SLEDs
  - Detectors: photodiodes, solar cells, CCDs, etc.

Silicon wafer: ingot growth

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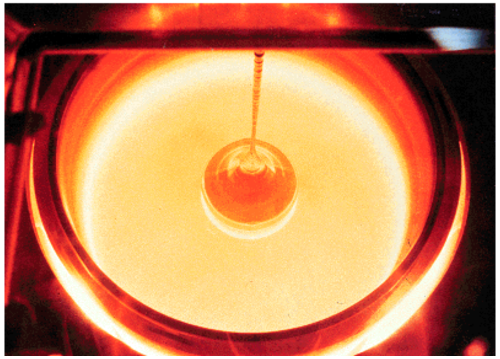
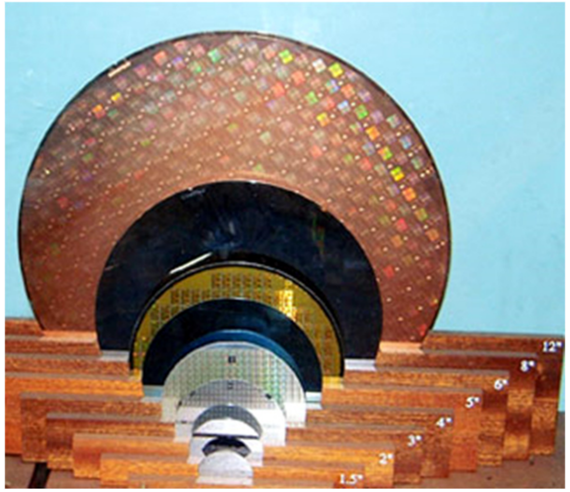


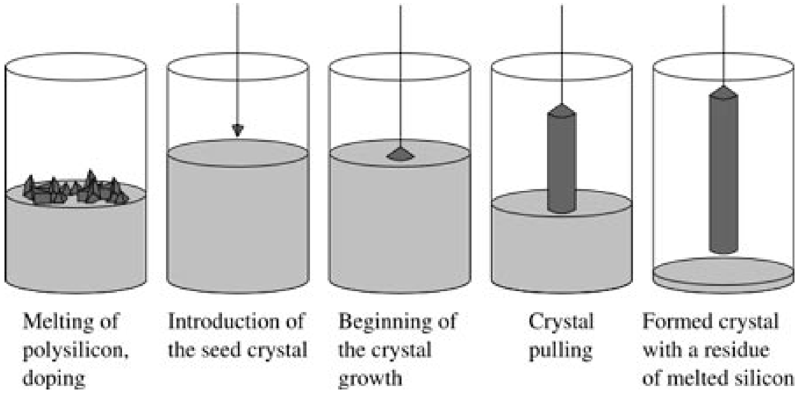
Czochralski growth (1916)

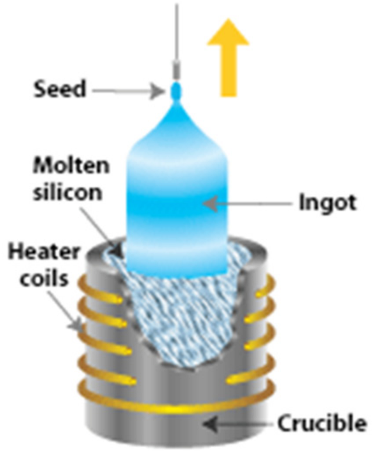


Increasing wafer diameters

Silicon wafer: ingot growth

Main steps of the Czochralski process





Crucible (quartz)

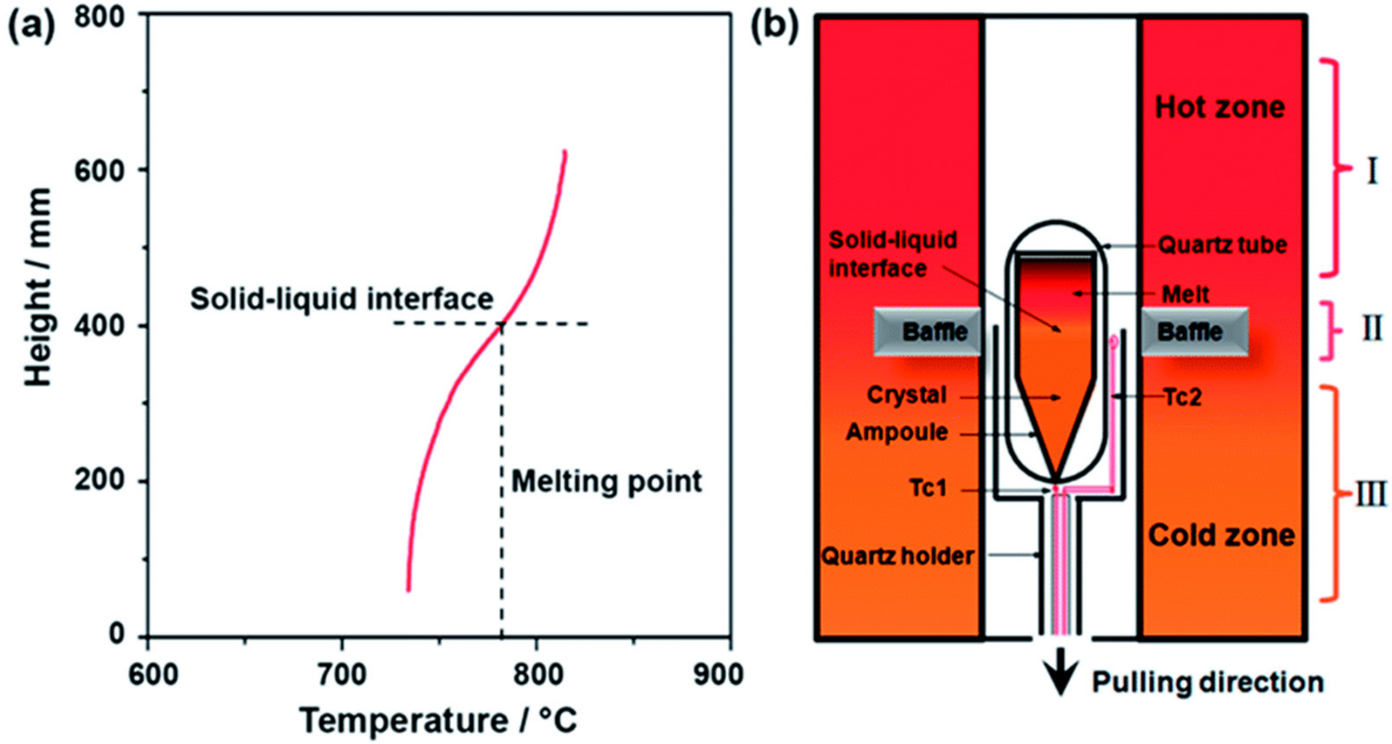
Argon + 1500°C

Crucible after being used

- Incorporation of oxygen impurities (precipitates acting as traps for unwanted transition metal impurities)
- Enhanced mechanical strength and radiation hardness

Alternative growth technique

Bridgman-Stockbarger process

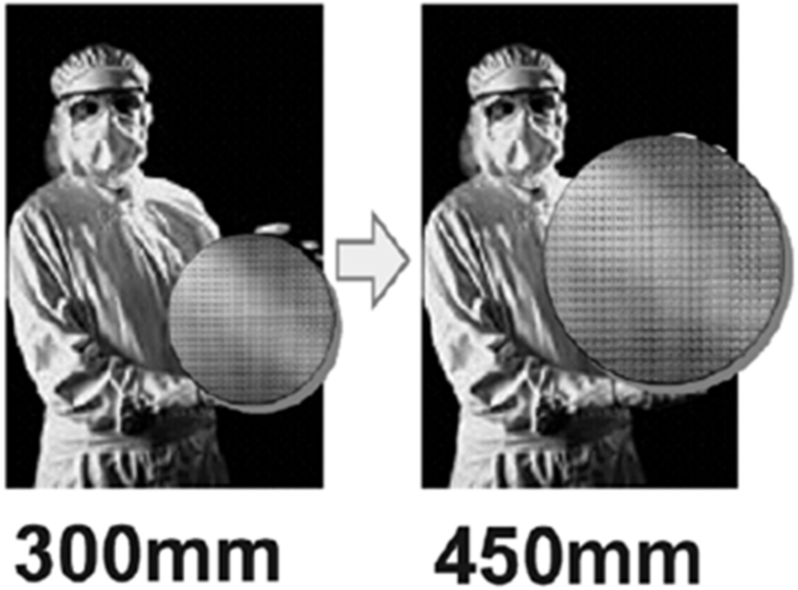


Heating a polycrystalline material above its melting point + slow cooling from one end of its container where a crystal seed is located (preferred to Czochralski process for GaAs ingots (lower defect density))

Silicon wafer: standard

Wafer size increases

About every 10 years…



Slowdown of this trend due to engineering, time and cost issues!

Wafer thickness is determined by the mechanical strength of the material used. The wafer must be thick enough to support its own weight without cracking during handling.

Main elementary semiconductors: Si, Ge and C

Element	Lattice parameter (Å)	Bandgap (eV)
C	3.567	5.47
Si	5.431	1.12
Ge	5.646	0.66
α-Sn	6.489	0

First hint about the origin of the bandgap and its magnitude!

The **octet rule** is a chemical rule of thumb that reflects observation that atoms of main-group elements tend to combine in such a way that each atom has eight electrons in its valence shell (same electron configuration as a noble gas).

The electrons shared by the two atoms in a covalent bond are counted twice, once for each atom.

Main compound semiconductors

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

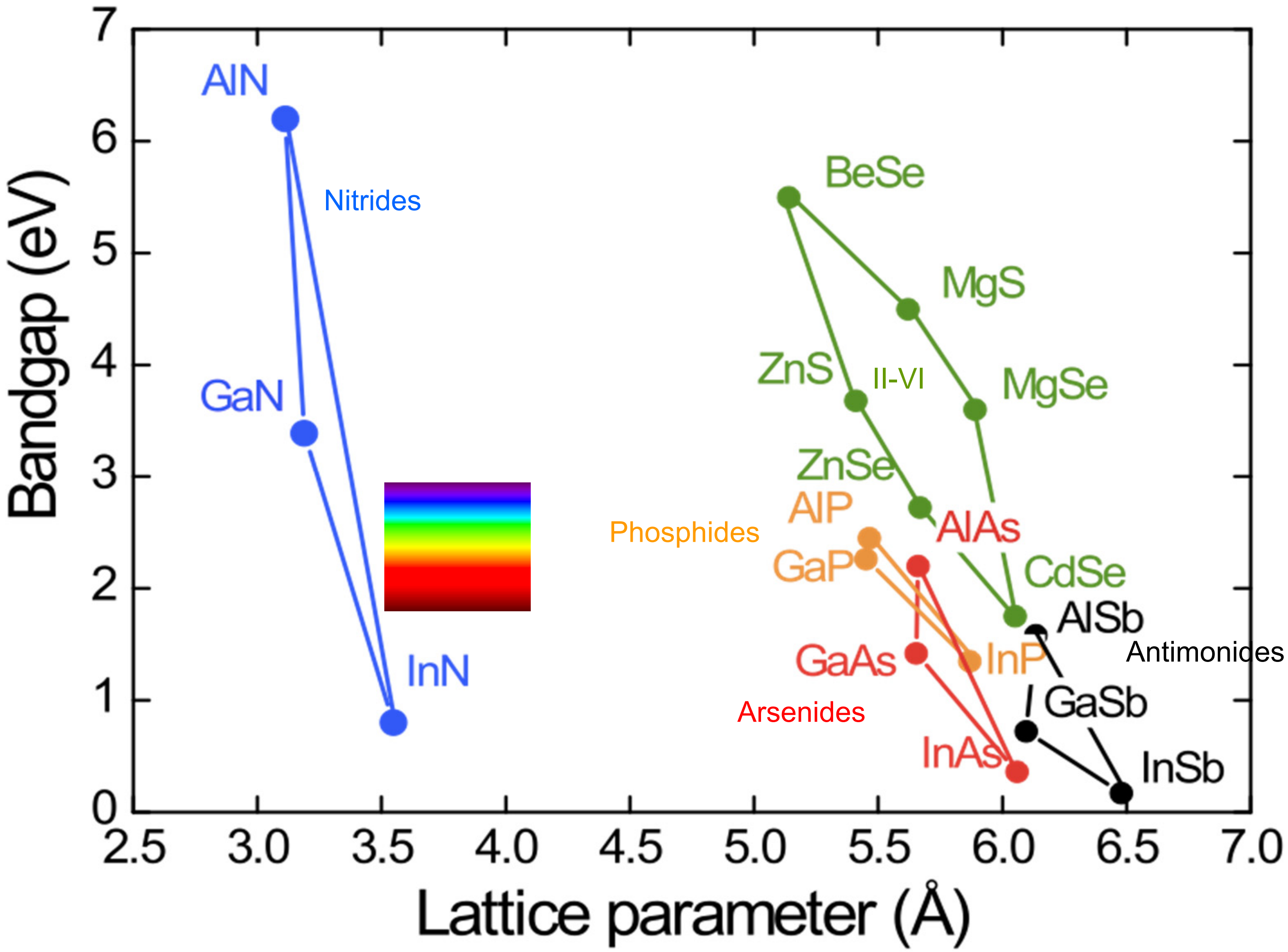
Compound semiconductors: $A_N B_{8-N}$

IV-IV: Si, Ge

III-V: GaAs, GaN, InP, etc.

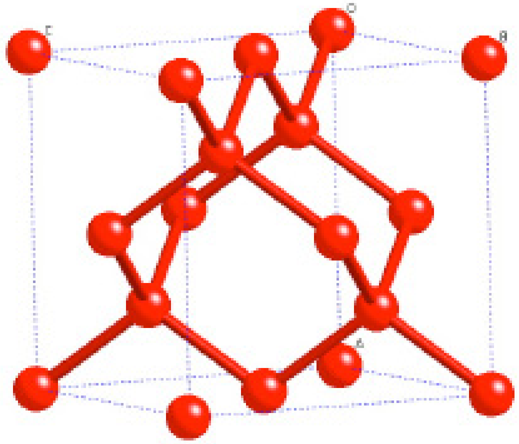
II-VI: ZnSe, CdTe, ZnO, etc.

Main compound semiconductors



Main semiconductors

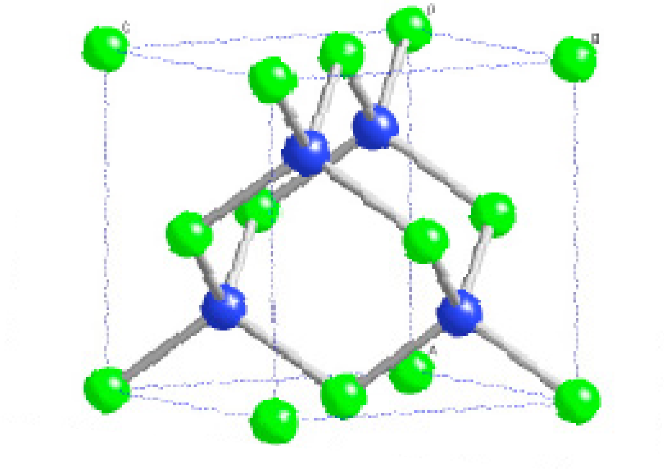
Crystal structures



Si

Diamond-like

2 interpenetrating fcc lattices

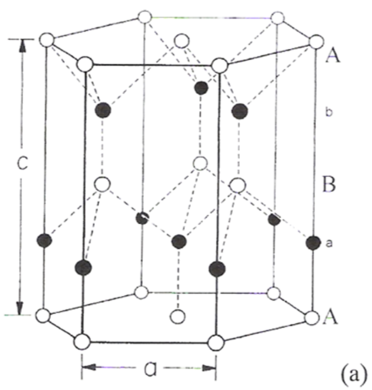


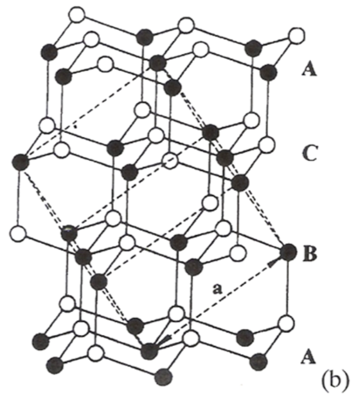
GaAs

Zinc-blende-like

Bandgap and crystal structure

ABAB… stacking





ABCA… stacking

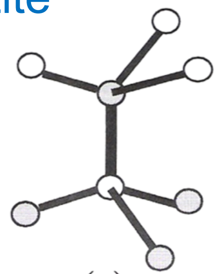
Thermodynamically stable phase

Wurtzite

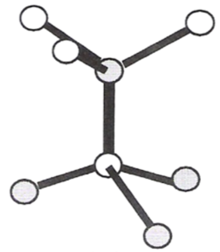
Zinc-blende

Case of GaN

E_g = 3.4 eV



(a)

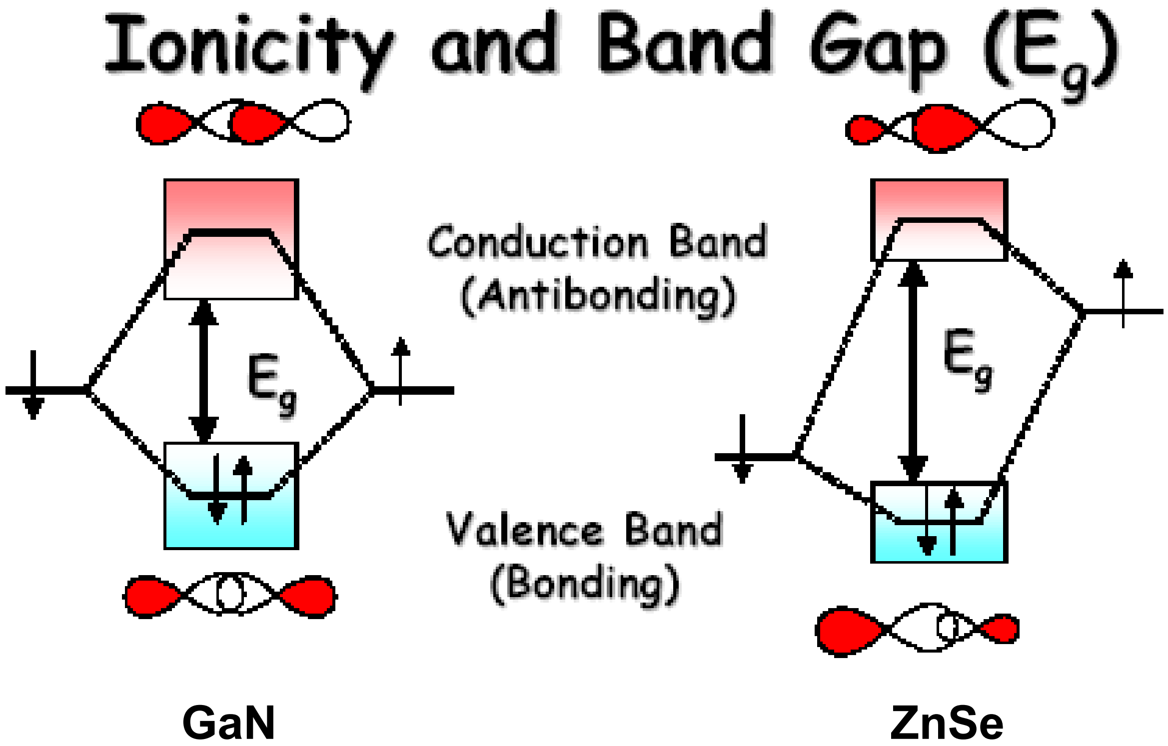


(b)

E_g = 3.2 eV

The bandgap depends on the crystal phase!

Electronegativity



Covalent: strong overlap
$\Rightarrow$ *large E_g and E_b*

Ionic: marginal overlap
$\Rightarrow$ *large E_g due to the increased electronegativity but small E_b*

E_b is the bond strength

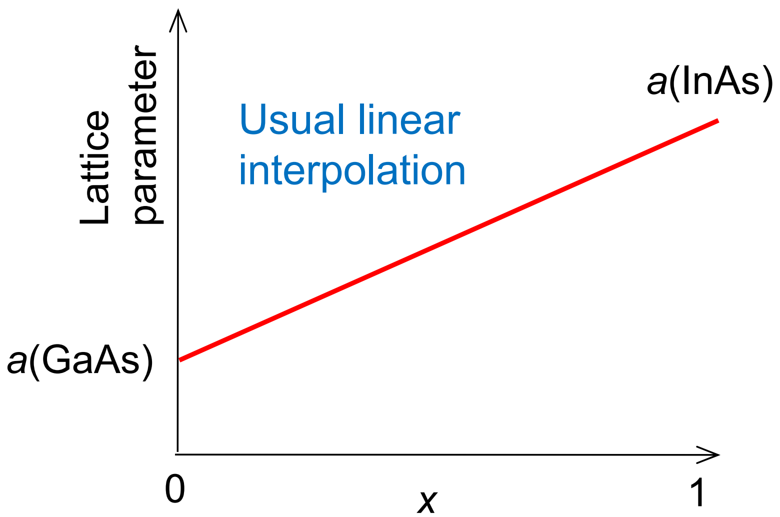
Alloy: Vegard’s law

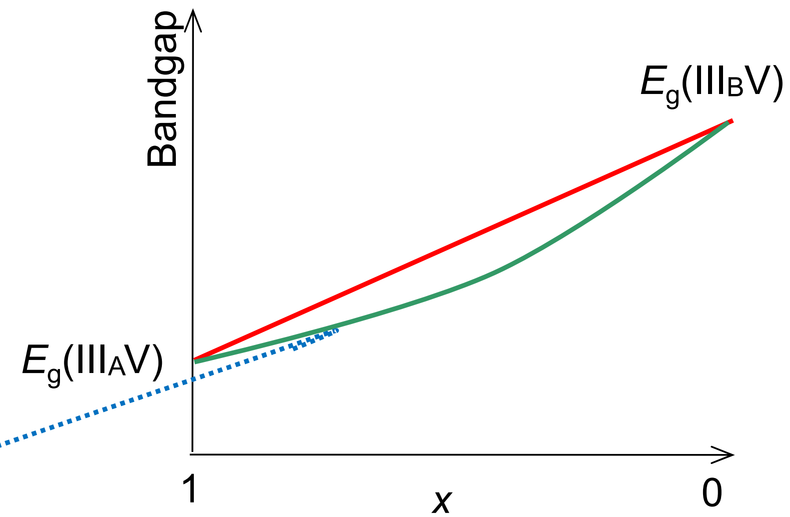
Example: GaAs and InAs ⇨ (Ga,In)As

- Indium atoms replace gallium ones and then the stoichiometry is conserved: 50% group-III elements, 50% group-V elements
- $In_xGa_{1-x}As$, with x the In composition

$$\boxed{a(In_xGa_{1-x}As) = x\, a(InAs) + (1-x)\, a(GaAs)}$$

The bandgap usually exhibits a deviation from a linear variation. This deviation might be important and must be accounted for by introducing a so-called bowing parameter.





Bowing: $E_g(In_xGa_{1-x}As) = x\, E_g(InAs) + (1-x)\, E_g(GaAs) - \mathbf{b}x(1-x)$