EE204FZ
Analog Electronics 1

Zhu DIAO

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Aims

- To provide an understanding of basic transistor electronics;
- To be able to analyse and design basic FET transistor circuits;
- To be able to construct a range of op-amp circuits.

In short, transistors (especially FETs) + op-amps

Learning Outcomes

- Explain the basic operating principles of a FET transistor (JFET and MOSFET);
- Construct small signal equivalent circuits for FETs;
- Design a small signal low frequency amplifier using FETs;
- Analyse and synthesise DC bias circuits for FET transistors;
- Construct and measure basic transistor circuits;
- Design and build a selection of basic operational amplifier circuits (integrator, adder, amplifier, etc.);
- Design a multi-stage filter using op-amps.

Course Module Contents

- Diode, JFET, and MOSFET;
- Basic FET circuits;
- Small signal model for basic FET amplifier;
- Design of basic digital logic gates from transistors;
- Background information on BJTs;

- Op-amps, DC and small signal behaviour;
- Basic op-amp circuits, including amplifiers, adders, integrators, and differentiators;
- Advanced op-amp circuits including multi-stage filters;
- Bode plots for op-amp circuits design.

Assessment Criteria

- Semester examination: 70%
- Laboratory (6): 30% (cannot be repeated)

The Pass Mark is 40% - one is not required to pass the written and continuous components separately.

Penalties: Late submission is subject to a penalty of 10% each day.

Lab Sessions & Lab Reports

- Reports with high similarity scores will be rejected (either you copied, or you were copied).

- Moodle *Turn-it-in* will be used. Turn-it-in allows for checking submitted pieces of writing for potential instances of plagiarism.

Teaching Schedule

- Learning Management System (LMS): Moodle;
- 28 lectures + 4 tutorials (week 1 – 16);
- 6 laboratory sessions (even weeks starting in week 4);
- Remote learning -> face-to-face instruction;
- Language of instruction: English.

How to Fail this Module?

- Do not turn up for your labs or do not turn in your assignments.

  Labs are very important for this course module.

  Instant loss of 30% of your final grade.

- Do not show up for your lectures.

  My own experience at university tells me that if one does not show up in lectures, it is highly unlikely that one uses this time to study.

- Do not ask questions.

  I understand that it is difficult to feel the existence of the instructor in a remote learning environment. But please try to keep contact with me as much as you can.

Textbooks

- Sedra & Smith, "*Microelectronic Circuits*", 5th Edition, Oxford University Press (2004).

  ISBN: 0195142527
- Ramakant A. Gayakwad, "*Op-Amps and Linear Integrated Circuits*", 4th Edition, Prentice Hall (2000).

  ISBN: 0132808684

- There are many alternative textbooks in the market. Many of them are of high quality. Feel free to choose a textbook that suits you the best.

Who am I?

- My name is **Zhu DIAO** (刁竹). I am a Lecturer in Electronic Engineering at Maynooth University.
- I'm Chinese and I did my undergraduate in China. I studied, lived and worked in Ireland, Sweden, Canada, and the US for >15 years before deciding to move back to Ireland this year.

EE204FZ
Lecture 1
Solid State Electronics
Brief Refresher

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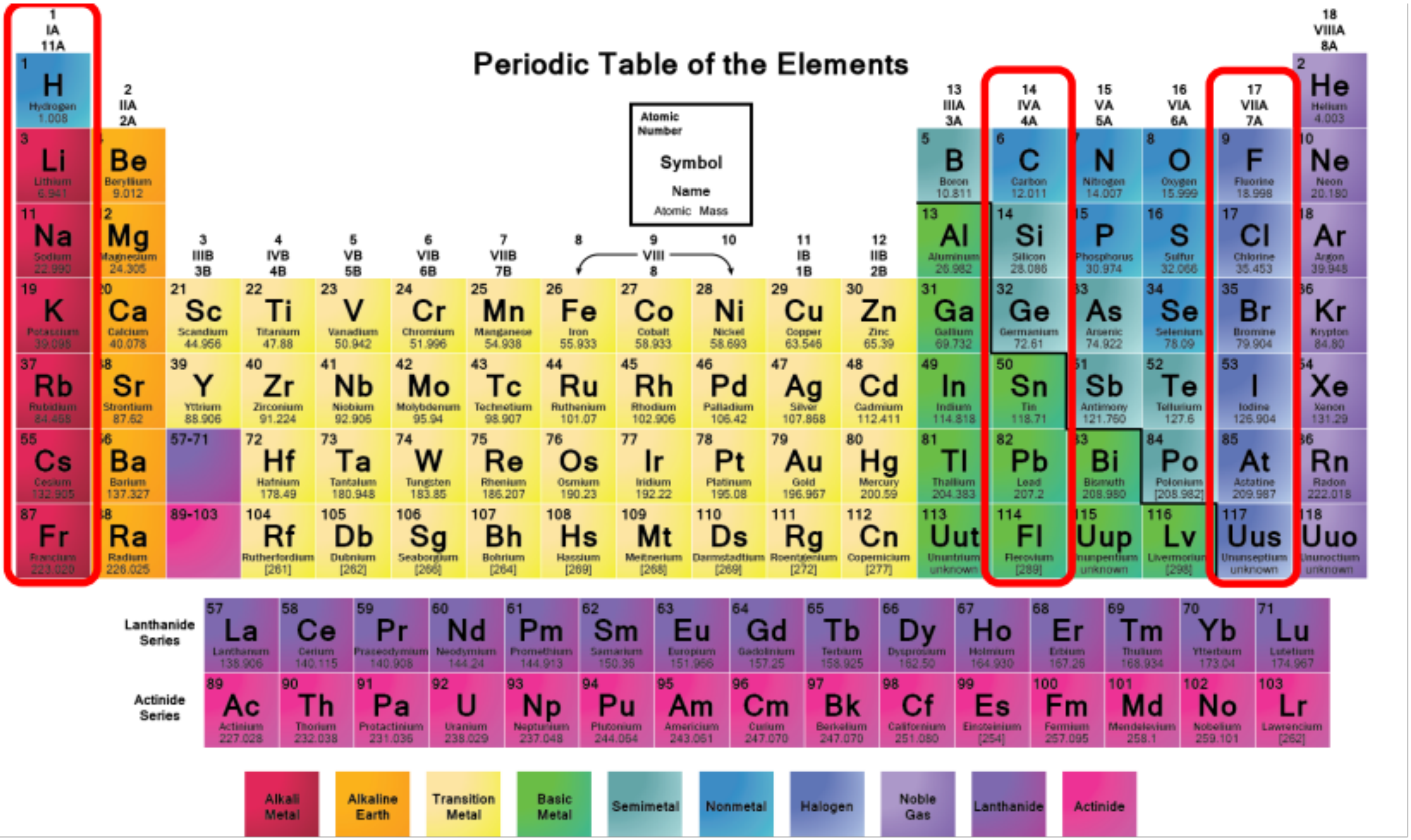
Objectives of This Lecture

- Electronic devices are made of semiconductor materials;

- In order to understand how these devices work, you should have a very basic knowledge of atomic structures and the interaction of atomic particles.

Periodic Table



Bohr Model of Atoms (1913)

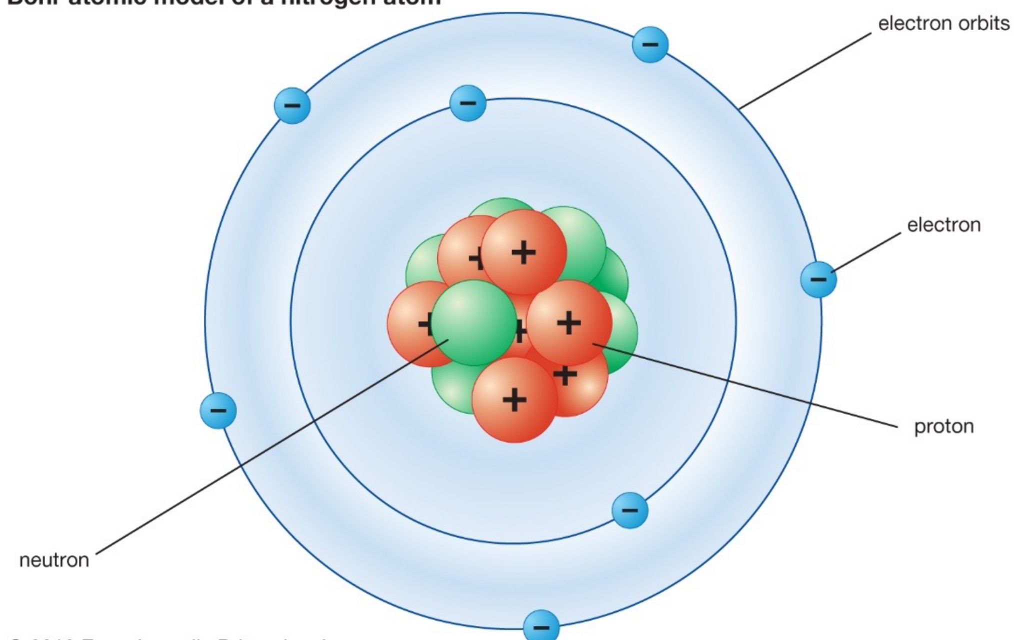
- Three subatomic particles:
  - Protons (+);
  - Neutrons (0);
  - Electrons (-).

Protons and Neutrons: Nucleus (+)

- Atomic number (Z):
  - Number of protons;
  - Number of electrons in a neutral atom.

  H: $Z = 1$

  Si: $Z = 14$



Other Important Terms

- Masses: Protons and neutrons have nearly the same mass (1.67×10^{-27} kg); The mass of an electron is much smaller (9.11×10^{-31} kg), neglected in atomic mass calculation; the atomic mass is approximately equal to the mass of protons plus the mass of neutrons;
- Isotope number = number of neutrons;
- AMU (Atomic Mass Unit or dalton): defined as 1/12 of the most common isotope of carbon atom having 6 protons and 6 neutrons, ^{12}C atom is 12 AMU;
- Atomic weight: ratio of the average mass of a chemical element's atoms (account for isotopes) to AMU, e.g., atomic weight of Si = 28.0855 AMU.

Electrons & Shells

- Electrons orbit the nucleus of the atom at a certain (averaged) distances from the nucleus;
- This distance corresponds to a discrete energy level;
- These are known as shell numbers or principal quantum numbers (*n*): 1, 2, 3, … and 1 being closest to the nucleus;
- If the proton in a hydrogen atom was the size of a golf ball, the electron shells would be approximately 1 mile (≈ 1600 m) away (diameter of hydrogen nucleus = 1.8 fm & diameter of hydrogen atom = 53 pm).

Quantum Numbers for Electron Shells

- Electrons fill the shells following certain rules and these rules are defined by quantum mechanics:
  - Shell or principal quantum number (n): 1, 2, 3, 4, …
  - Orbital momentum quantum number (ℓ): 0, 1, 2, …, (n-1)
  - Magnetic quantum number (m_l):
    $-\ell$, $(-\ell+1)$, $(-\ell+2)$, …, 0, …, $(\ell-2)$, $(\ell-1)$, ℓ
  - Spin quantum number (m_s): $\pm\frac{1}{2}$.

Can't remember? No problem.

The maximum number of electrons a shell with principal quantum number n can accommodate is $2n^2$.

Examples: Quantum Numbers

n	ℓ	m_l	m_s	Total Electrons
1 (K)	0 (s)	0	-1/2	2
			+1/2	
2 (L)	0 (s)	0	-1/2	8
			+1/2	
	1 (p)	-1	-1/2	
			+1/2	
		0	-1/2	
			+1/2	
		+1	-1/2	
			+1/2	

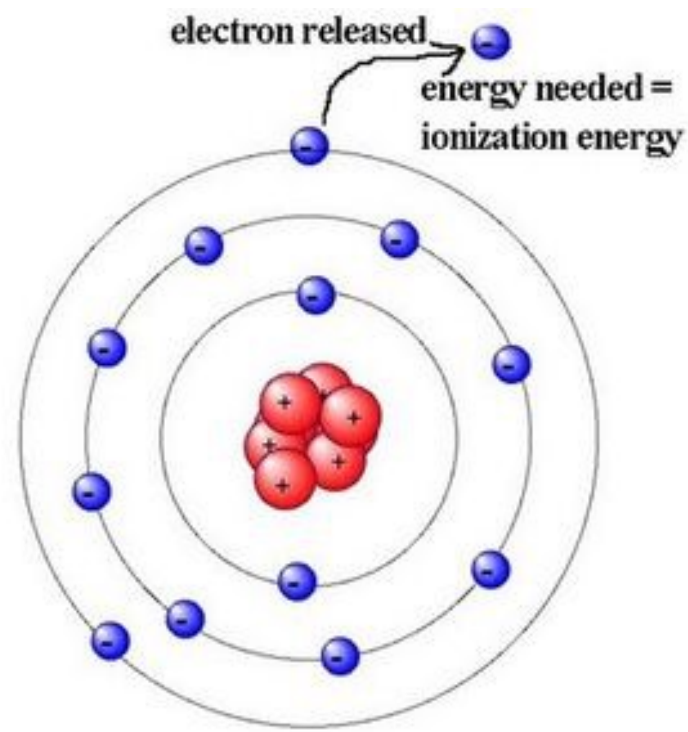
Feel free to verify the $2n^2$ rule yourselves.

Valence Shell

- Electrons that orbit in the outermost shells and furthest from the nucleus have the highest energy levels and are less tightly bound to the atom;
- They are easier to be displaced from the atom;
- Outermost shell is known as the valence shell and electrons in the valence shell are valance electrons;
- The process of losing a valence electron is called ionisation.

Ionisation

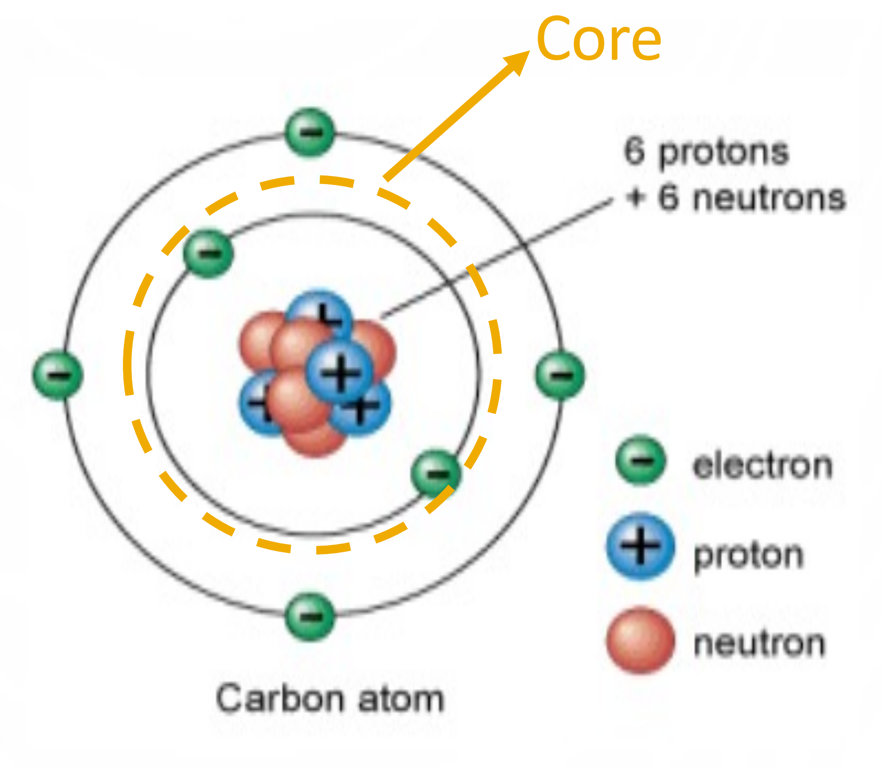
- When an atom absorbs energy, the electron energies are raised. The valence electrons possess more energy and are more loosely bound to the atom than the inner electrons, so they can actually escape from the outer shell and the atom influenced.



https://ellesmere-chemistry.fandom.com/wiki/Ionisation_Energy

Valence Shell & Electrical Properties

- For the purpose of discussing electrical properties, an atom can be represented by the valence shell and a core that consists of all the inner shells and the nucleus. For example, a carbon atom has a core with a net charge of +4 elementary charge.

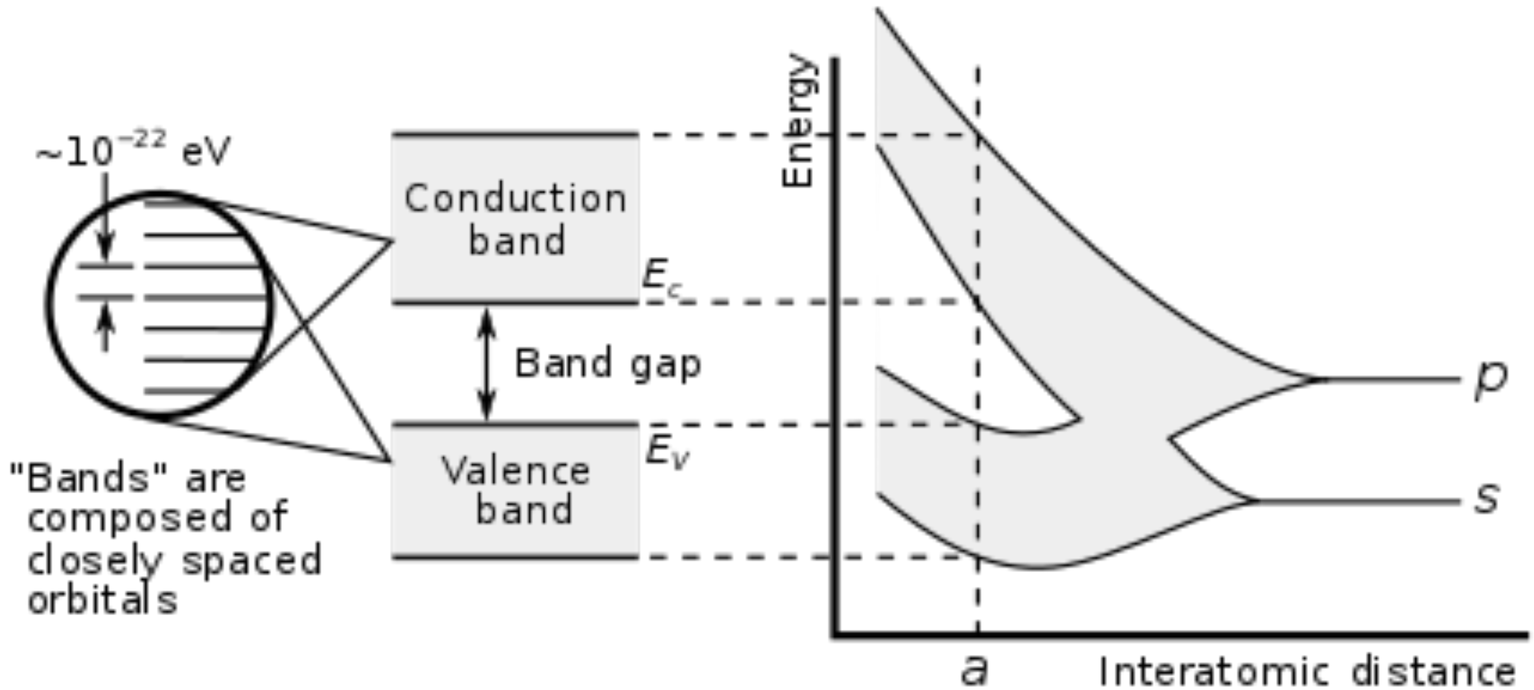


Energy Band

- Electrons in single, isolated atoms occupy atomic orbitals which have discrete energy levels;
- When *N* atoms ($N \approx 10^{22}$) come together to form solids, each of their atomic orbitals splits into *N* discrete (molecular) orbitals whose energy levels are very closely spaced -> energy band.
- Energy band forms due to the Pauli exclusion principle (no two electrons in the solid can have exactly the same quantum numbers).

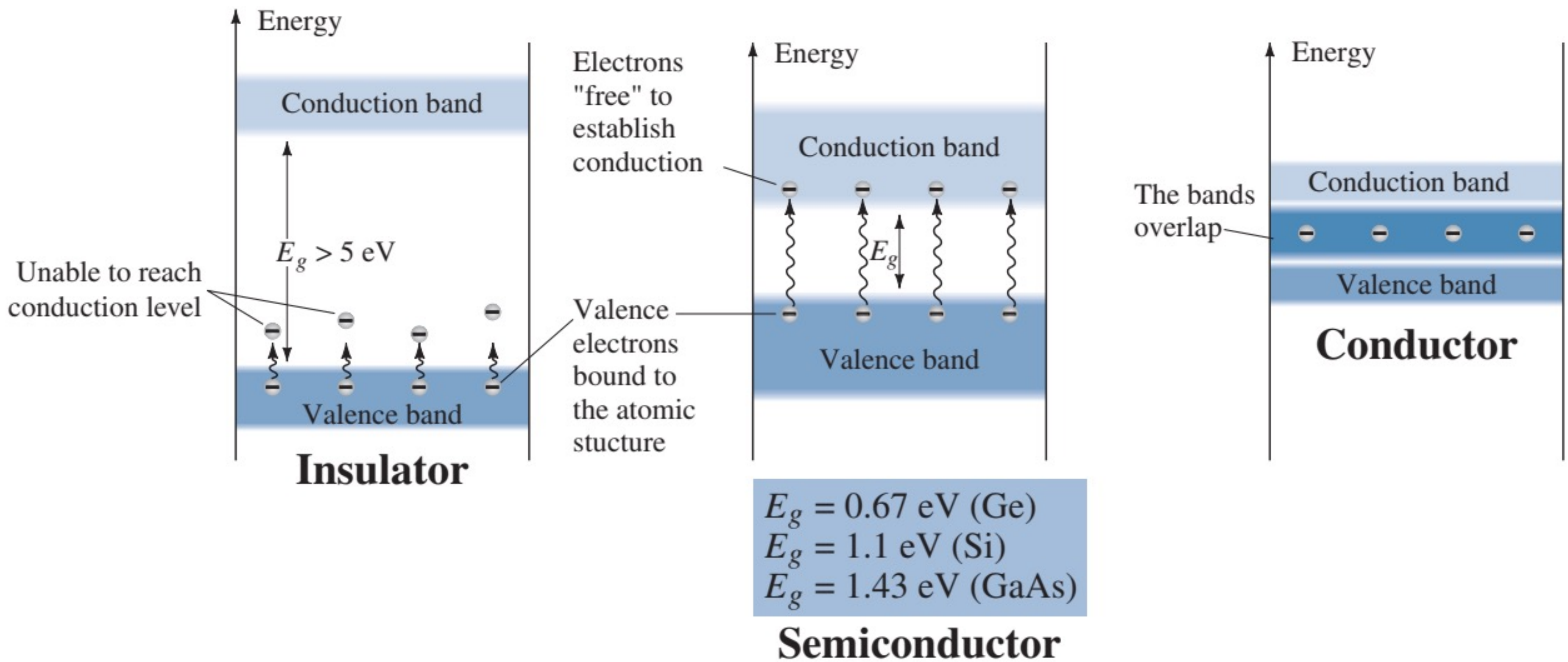
Band Gap (Energy Gap)

- **Band gap** is a range of energy in a solid where no electronic states can exist.



https://en.wikipedia.org/wiki/Electronic_band_structure

Metals, Insulators & Semiconductors

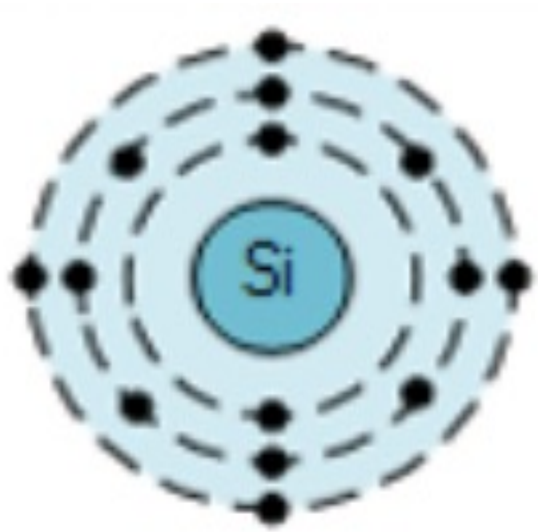


Metals, Insulators & Semiconductors

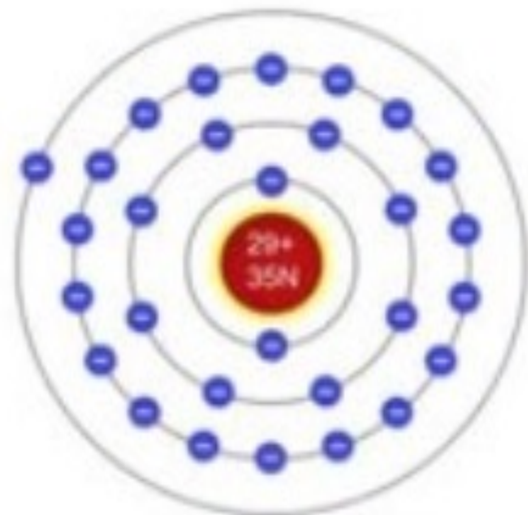
- An insulator is a material that does not conduct electrical current under normal conditions (rubber, plastic, glass);
- A conductor is a material that easily conducts electrical current (copper, silver, gold);
- A semiconductor is a material that is somewhere between an insulator and a conductor (silicon).

Semiconductor Atom *vs*. Conductor Atom

Silicon (semiconductor)



Copper (Conductor)

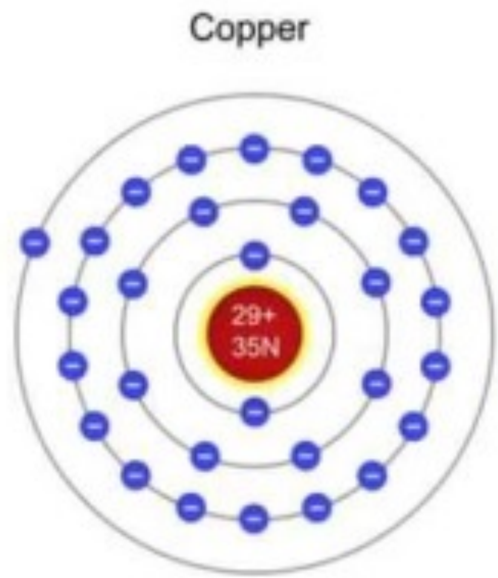


- Note that the silicon core has a +4 net elementary charge while the copper core has +1 net charge. There is more force trying to hold valence electrons to the atom in silicon than in copper.

Conductor

What makes copper a good conductor?

- Copper has an atomic number of 29.
- It has one electron in its valence shell.
- Easy for it to shed its outer electron and the previous shell is complete.
- This free electron is used to conduct electricity.



Ideal State

- In an ideal state, each atom will have a full outer (valence) shell;
- Atoms may give away a few electrons to expose an underlying complete shell;
- Atoms may also accept a few electrons to complete the outer shell;
- A simpler solution is to ‘share’ electrons among atoms.

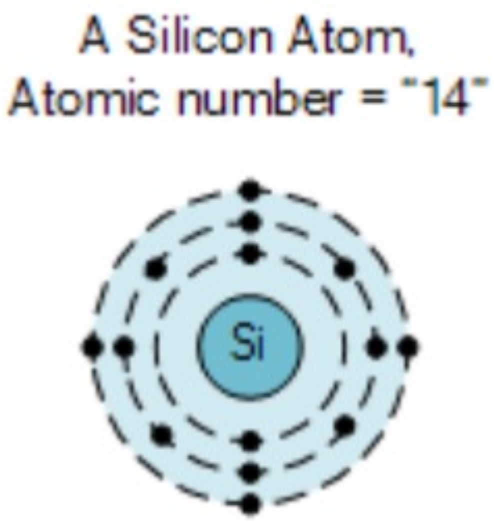
Silicon (Z = 14)

2 electrons in the 1 – shell

8 electrons in the 2 – shell

4 electrons in the 3 – shell (valence)

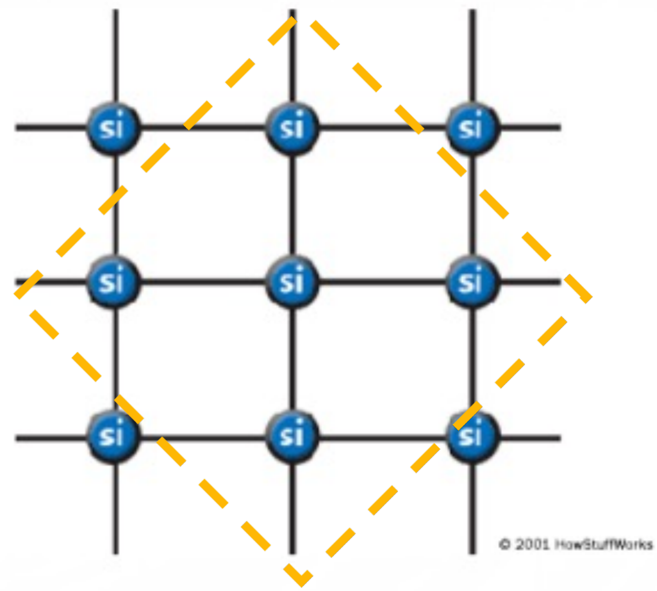
14 = Atomic number.



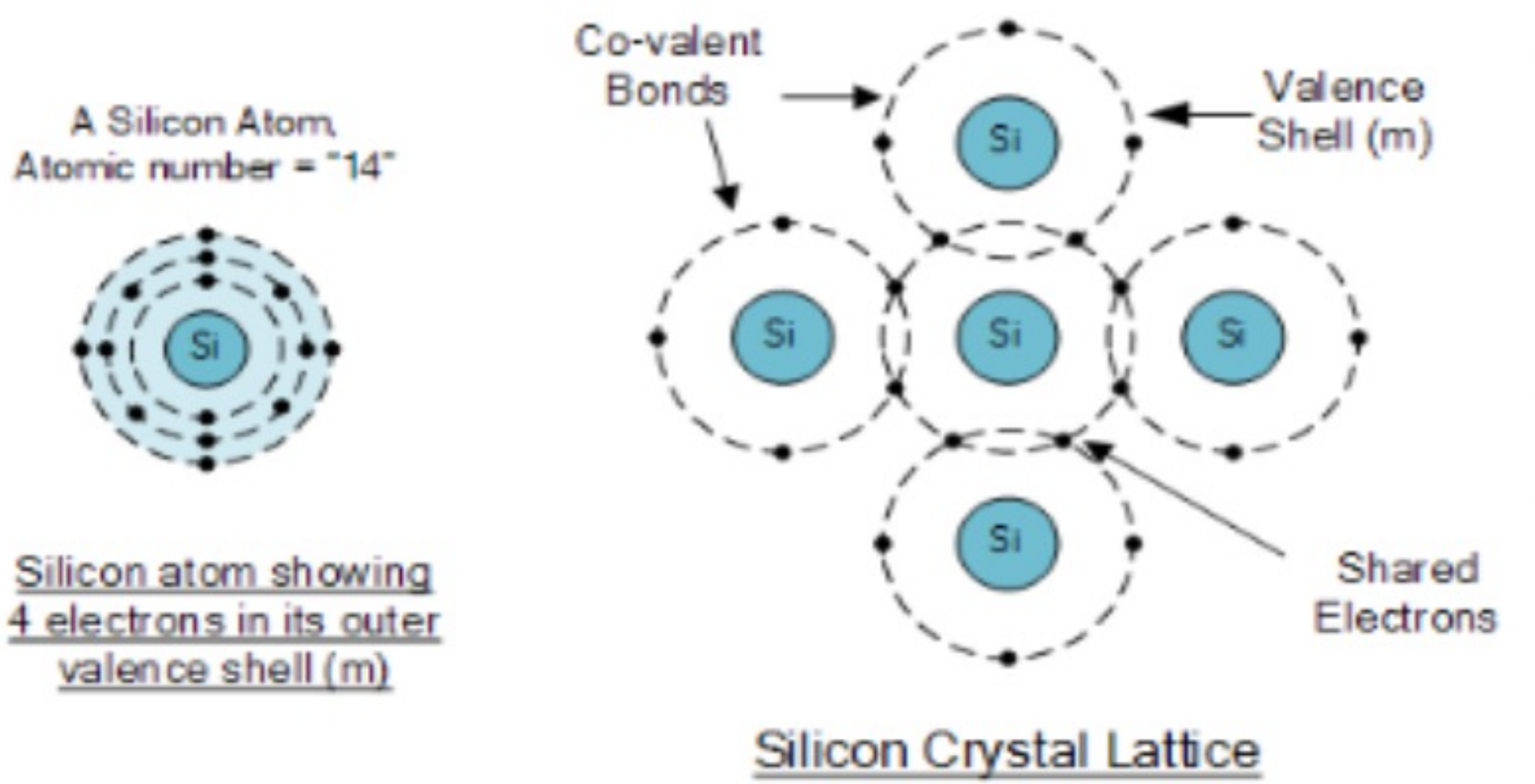
Silicon ($Z = 14$)

5 Silicon atoms come together to share the single electron in the valence.

Thus each atom now thinks that it has a complete valence shell with 8 electrons



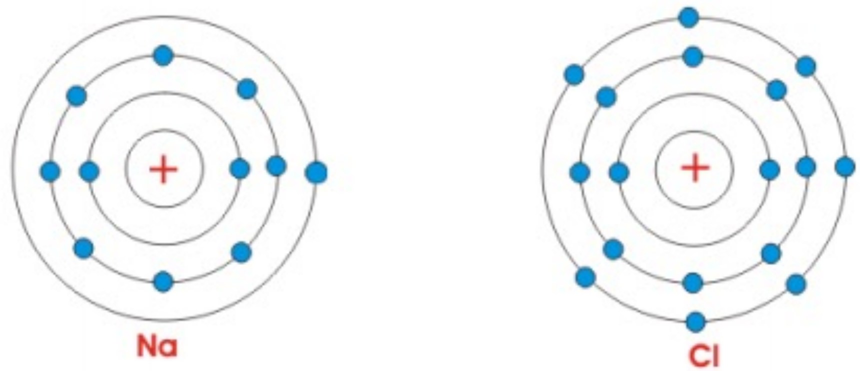
Silicon (Z = 14)


A Silicon Atom,
Atomic number = "14"
Si
Silicon atom showing
4 electrons in its outer
valence shell (m)
Co-valent
Bonds
Valence
Shell (m)
Shared
Electrons
Silicon Crystal Lattice

Electron Sharing

ELECTRON SHARING

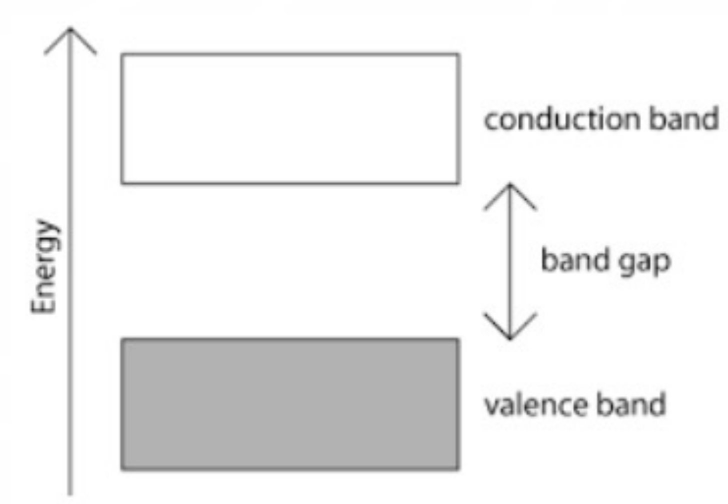
- Let’s have a look at electron sharing with 2 dissimilar elements
- Sodium (Na) is a group 1 element with one electron in its outer shell.
- Chlorine (Cl) is a group 7 element with 7 electrons in it outer shell.



- NaCl is table salt.

Current in Semiconductors

- In an unexcited (no external energy such as heat) atom, there are no electrons in the conduction band. This condition occurs <u>only</u> at 0 Kelvin.
- At room temperature (300 K), some valence electrons bridge the gap into the conduction band and become conduction electrons. The vacancy left in the valence band is called a hole.
- Recombination occurs when an electron in the conduction band loses energy and falls back into the valence band (eliminates an electron-hole pair).



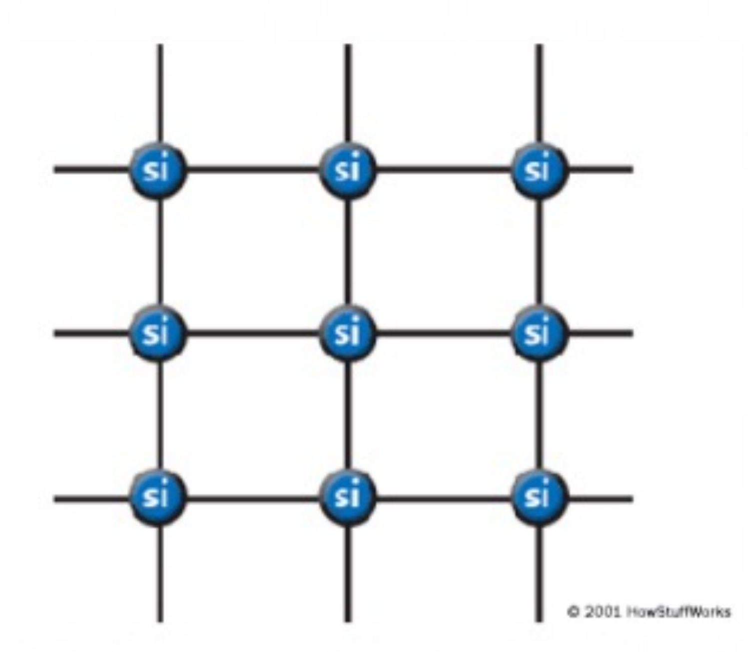
Electron & Hole Current

- When a voltage is applied across a piece of intrinsic semiconductor, the previously generated free electrons in the conduction band are attracted towards the positive end -> electron current.

- Hole current moves towards the negative end.

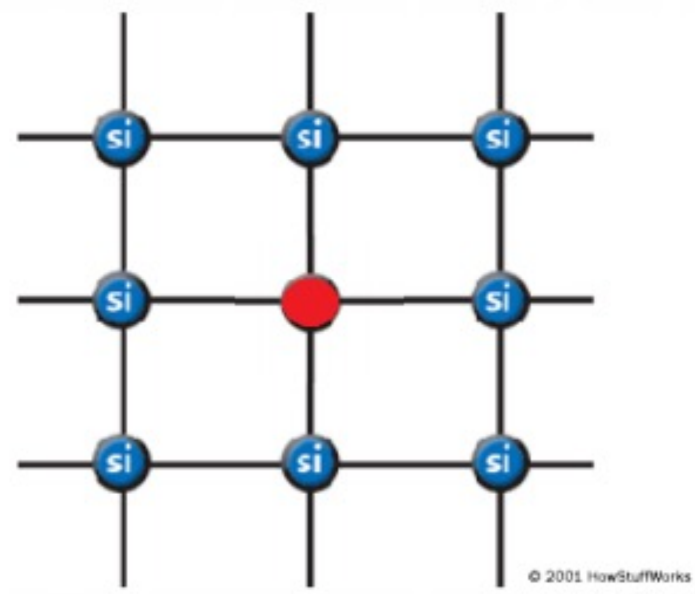
Intrinsic Semiconductors (Pure)

- Intrinsic semiconductors are made up of all the same atoms, i.e., silicon.
- The silicon atom has 4 electrons in the valence shell and it shares with 4 adjoining silicon atoms to fulfill its outer shell.
- This is known as covalent bond and it is electrically neutral.



Extrinsic Semiconductors (Impure)

- In order to drastically improve the conductivity of a semi-conductor we add impurities to the intrinsic atoms.
- This is called doping.
- This produces two types of materials:
  - n-type (negatively charged carriers)
  - p-type (positively charged carriers)



n-type Doping

Lets start with a pure Silicon (Si)

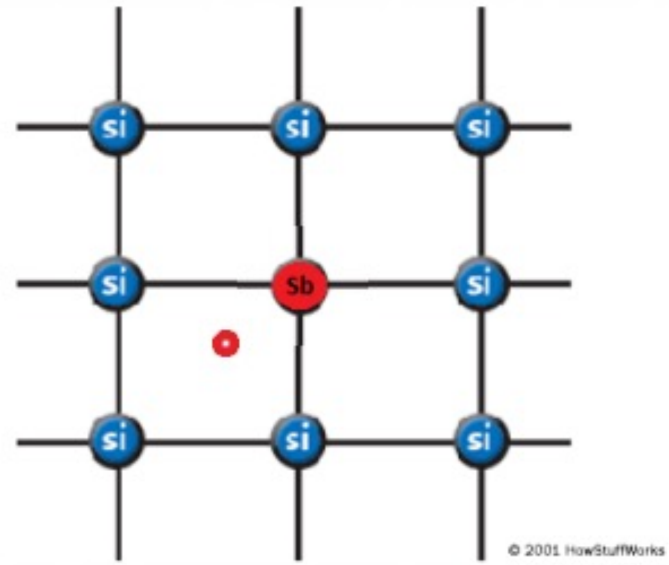
It has 4 electrons in it's Valence shell.

Introduce an Antimony (Sb)

This has 5 electrons in its valence shell.

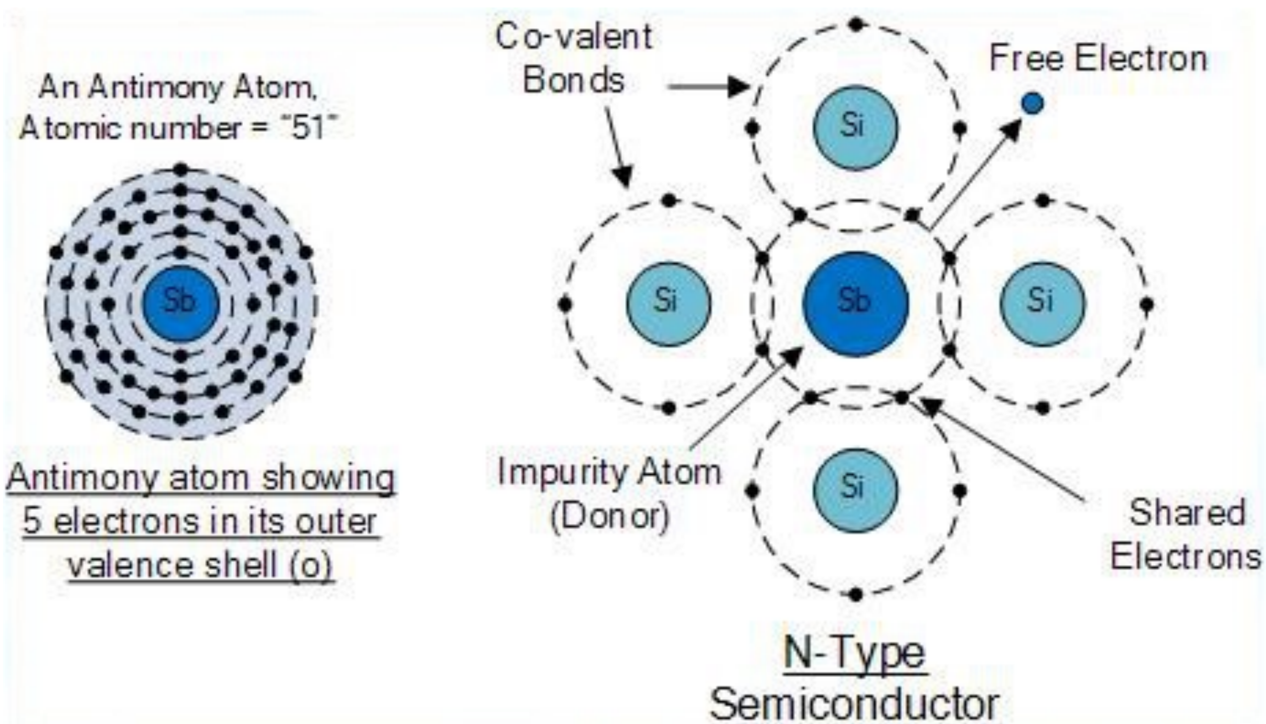
4+5 = 9 electrons in valence shell.

Too many => 1 free electron



n-type Dopant

- Antimony (Sb), Arsenic (As), Phosphorous (P), and Bismuth (Bi) are all known as pentavalent impurity atoms, i.e., they have 5 valence electrons.



https://tutorialslink.com/library/Getting-Started-with-Basic-Electronics/P-and-N-Type/23/399

p-type Doping

Again let's start with a pure Silicon (Si)

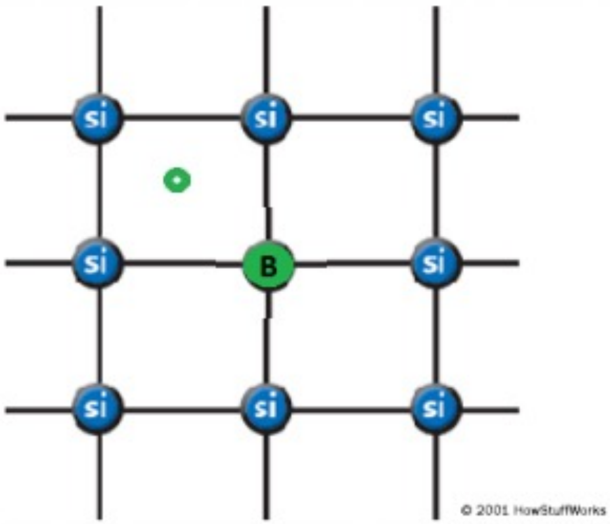
It has 4 electrons in it's valence shell.

Introduce a Boron (B)

This has 3 electrons in its valence shell.

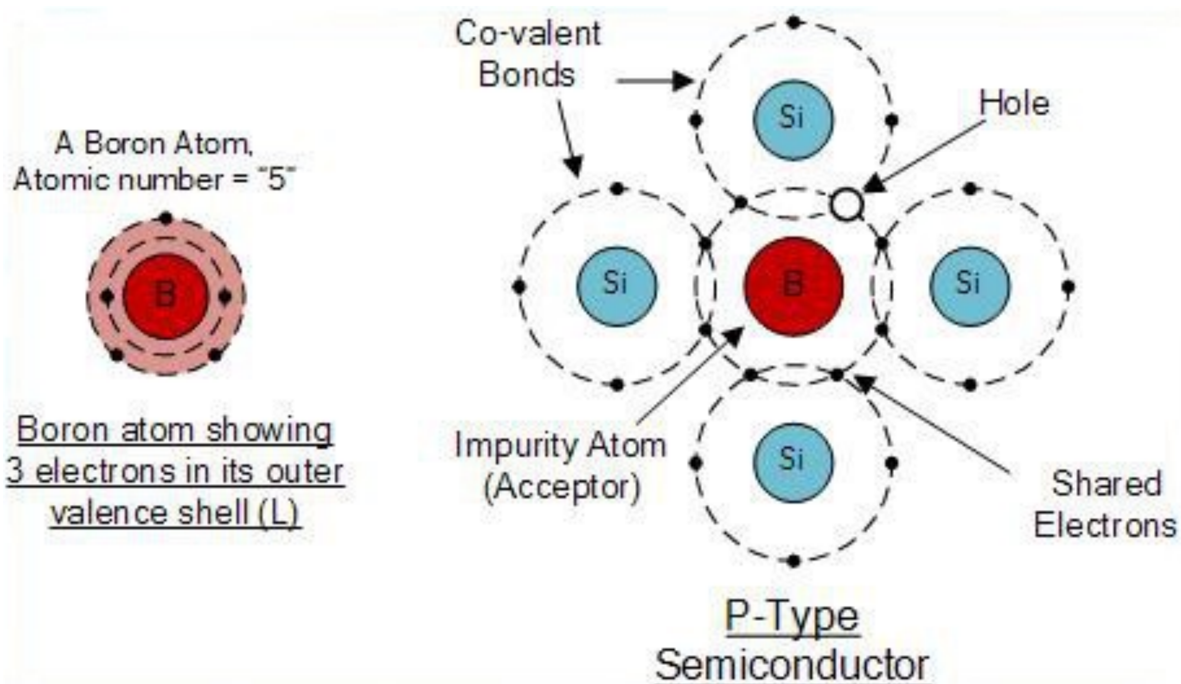
4+3 = 7 electrons in valence shell.

Too little=> 1 missing electron (Hole)



p-type Dopant

- To increase the number of holes in intrinsic silicon, trivalent impurity atoms are added, i.e., atoms with 3 valence electrons such as Boron (B), Indium (In), and Gallium (Ga).



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Some Questions for You

- Q1: What is the difference between an intrinsic and an extrinsic semiconductor?
- Q2: If one adds phosphorous to silicon, what type of doping does one perform? How does it work?
- Q3: What is meant by the term band gap energy of a semiconductor?
- Q4: What is the valence band?
- Q5: What is ionisation?

What You Should Do After the Class

- Verify your access to Moodle.
- Go through the module syllabus.
- Review the most important information covered in solid state electronics.