

# EE204FZ

# Analog Electronics 1

Zhu DIAO

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# Aims

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- 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

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- 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

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- 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

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- 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

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- 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

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- 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?

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- 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

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- Sedra & Smith, “*Microelectronic Circuits*”, 5<sup>th</sup> Edition, Oxford University Press (2004).  
ISBN: 0195142527
- Ramakant A. Gayakwad, “*Op-Amps and Linear Integrated Circuits*”, 4<sup>th</sup> 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?

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- My name is **Zhu DIAO** (刁婷). 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

Zhu DIAO

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# Objectives of This Lecture

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- 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.

The image displays a comprehensive periodic table of elements, color-coded by groups. The groups are labeled at the bottom: Alkali Metal (red), Alkaline Earth (orange), Transition Metal (yellow), Basic Metal (green), Semimetal (light blue), Nonmetal (dark blue), Halogen (purple), Noble Gas (pink), Lanthanide (light purple), and Actinide (dark purple). The table includes element symbols, names, atomic numbers, and atomic masses. A legend box in the center defines the information provided for each element: Atomic Number, Symbol, Name, and Atomic Mass. The elements are arranged in rows and columns, with the Lanthanide and Actinide series shown separately at the bottom. The groups are labeled with Roman numerals and letters (e.g., 1A, 2A, 3A, etc.) at the top. The elements are color-coded by groups: Alkali Metal (red), Alkaline Earth (orange), Transition Metal (yellow), Basic Metal (green), Semimetal (light blue), Nonmetal (dark blue), Halogen (purple), Noble Gas (pink), Lanthanide (light purple), and Actinide (dark purple). The elements are arranged in rows and columns, with the Lanthanide and Actinide series shown separately at the bottom. The groups are labeled with Roman numerals and letters (e.g., 1A, 2A, 3A, etc.) at the top. The elements are color-coded by groups: Alkali Metal (red), Alkaline Earth (orange), Transition Metal (yellow), Basic Metal (green), Semimetal (light blue), Nonmetal (dark blue), Halogen (purple), Noble Gas (pink), Lanthanide (light purple), and Actinide (dark purple).

1 IA 11A	2 IIA 2A	Periodic Table of the Elements																13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A												
1 H Hydrogen 1.008																								2 He Helium 4.003											
3 Li Lithium 6.941	4 Be Beryllium 9.012																	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180												
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948											19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29																		
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine 209.987	86 Rn Radon 222.018																		
87 Fr Francium 223.029	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown																		
			57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967																		
			89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]																		

Legend:

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Basic Metal
- Semimetal
- Nonmetal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

# Bohr Model of Atoms (1913)

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

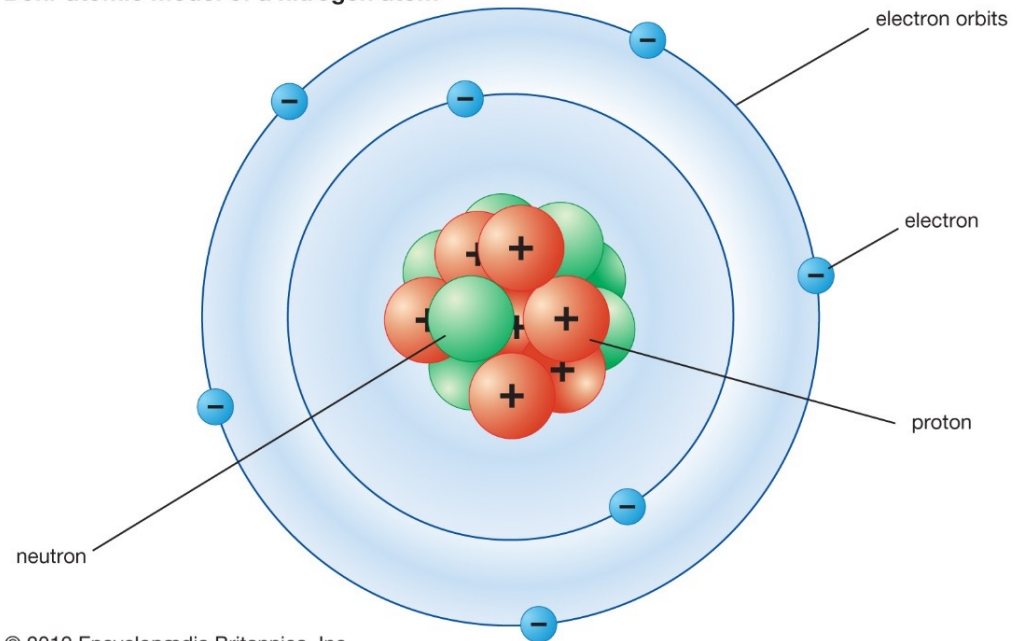
} Nucleus (+)

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

H:  $Z = 1$

Si:  $Z = 14$

Bohr atomic model of a nitrogen atom



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# Other Important Terms

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- **Masses**: Protons and neutrons have nearly the same mass ( $1.67 \times 10^{-27}$  kg); The mass of an electron is much smaller ( $9.11 \times 10^{-31}$  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,  $^{12}\text{C}$  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

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- 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 ( $\approx 1600$  m) away (diameter of hydrogen nucleus = 1.8 fm & diameter of hydrogen atom = 53 pm).



# Quantum Numbers for Electron Shells

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- 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 ( $\ell$ ): 0, 1, 2, ..., ( $n-1$ )
  - Magnetic quantum number ( $m_\ell$ ):  
 $-\ell, (-\ell+1), (-\ell+2), \dots, 0, \dots, (\ell-2), (\ell-1), \ell$
  - 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

$n$	$\ell$	$m_\ell$	$m_s$	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.

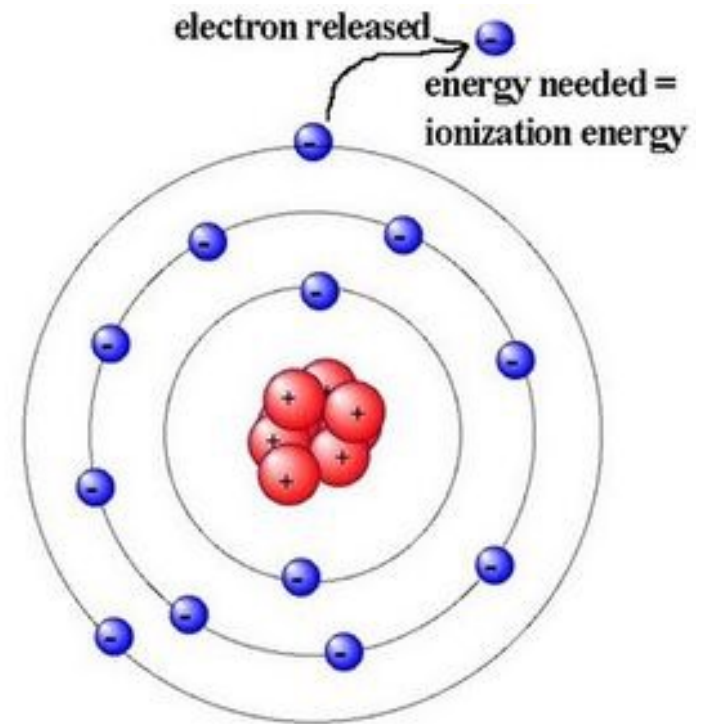
# Valence Shell

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- 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

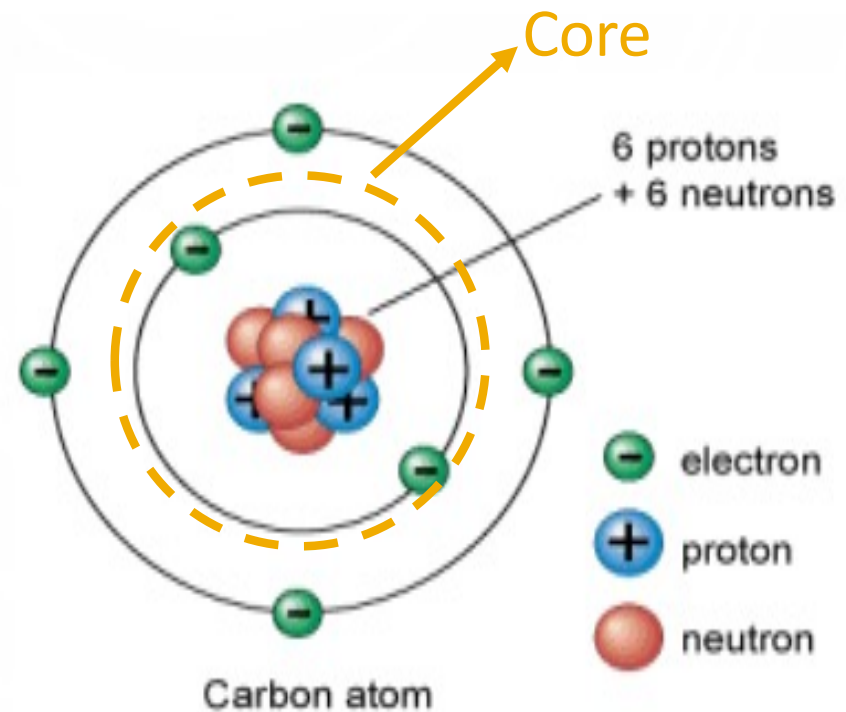
- When an atom absorbs energy, the electron energies are raised. The valence electrons possess more energy and are more loosely bound to the atom than the inner electrons, so they can actually escape from the outer shell and the atom influenced.



[https://ellesmere-chemistry.fandom.com/wiki/Ionisation\\_Energy](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.



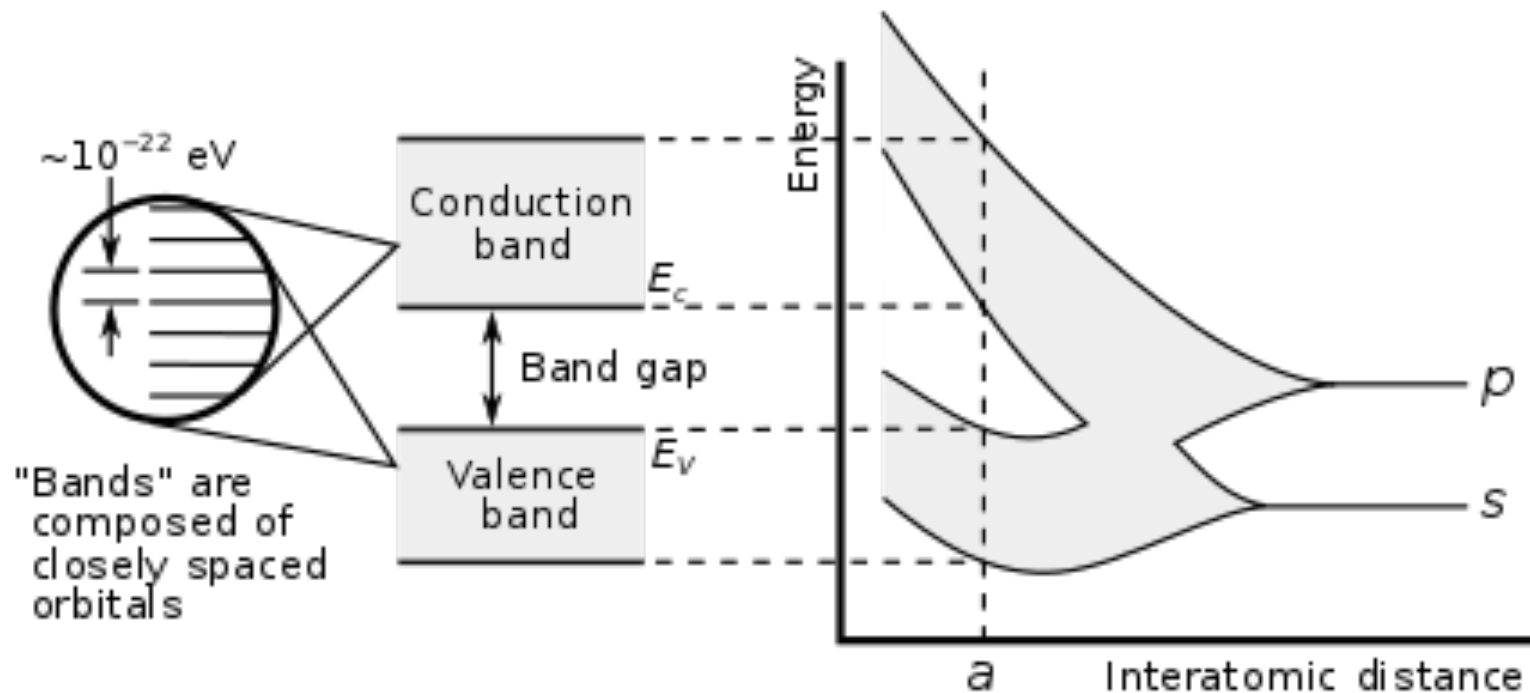
# Energy Band

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- 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).

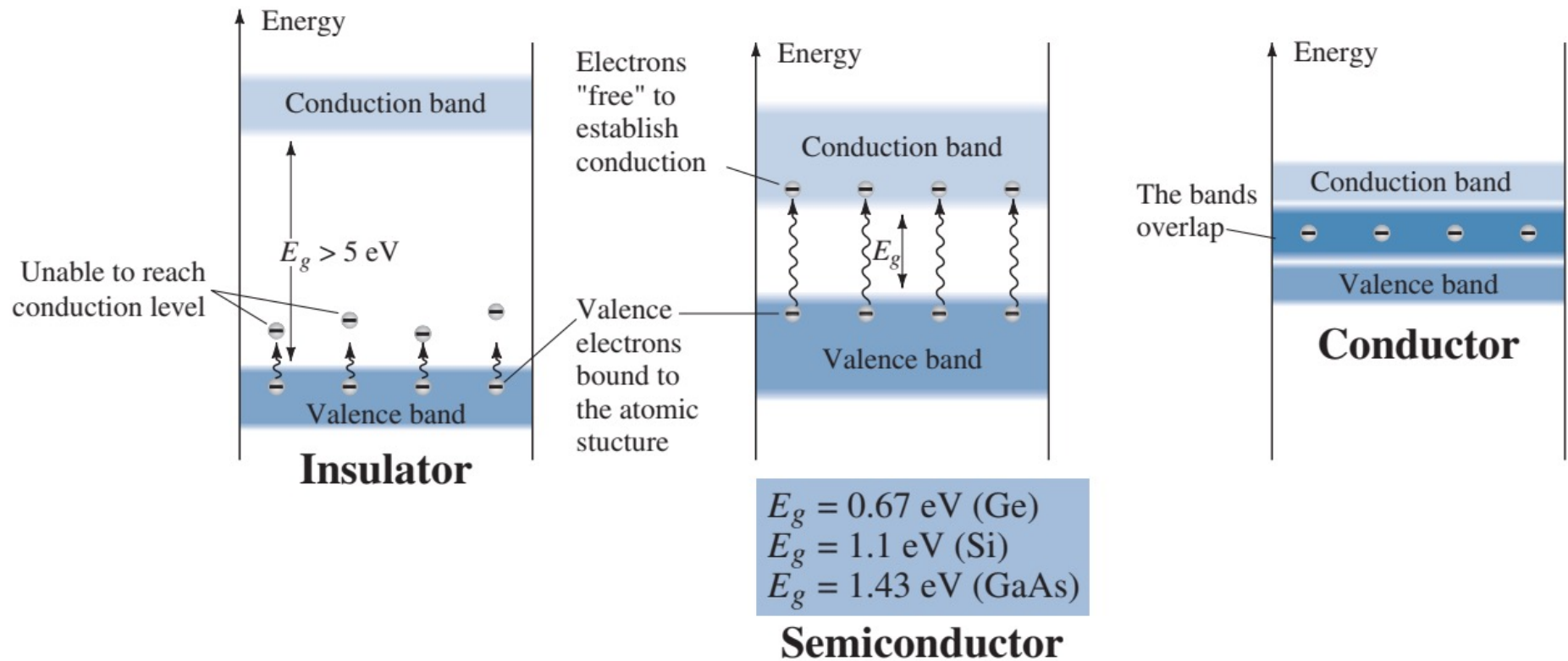
# Band Gap (Energy Gap)

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



[https://en.wikipedia.org/wiki/Electronic\\_band\\_structure](https://en.wikipedia.org/wiki/Electronic_band_structure)

# Metals, Insulators & Semiconductors





# Metals, Insulators & Semiconductors

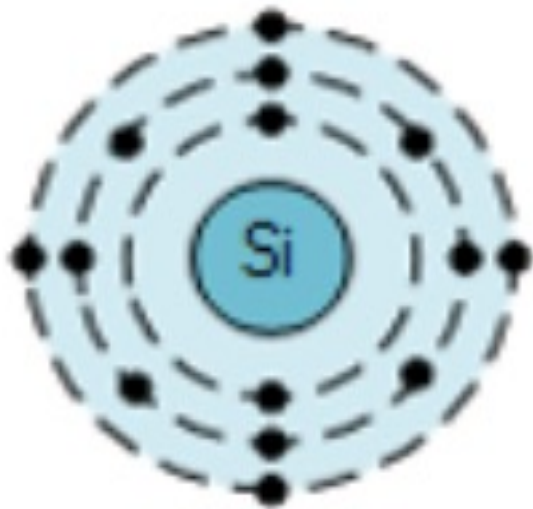
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- An **insulator** is a material that does not conduct electrical current under normal conditions (rubber, plastic, glass);
- A **conductor** is a material that easily conducts electrical current (copper, silver, gold);
- A **semiconductor** is a material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

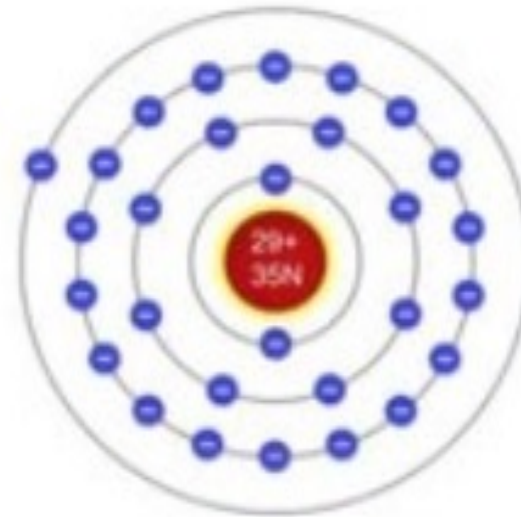
# Semiconductor Atom vs. Conductor Atom

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Silicon (semiconductor)



Copper (Conductor)



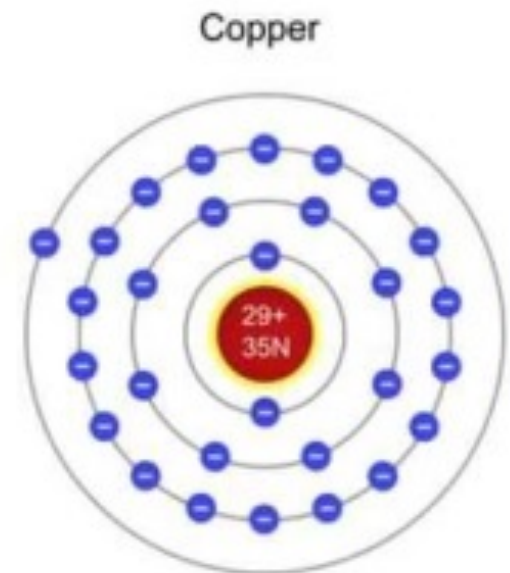
- Note that the silicon core has a +4 net elementary charge while the copper core has +1 net charge. There is more force trying to hold valence electrons to the atom in silicon than in copper.

# Conductor

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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

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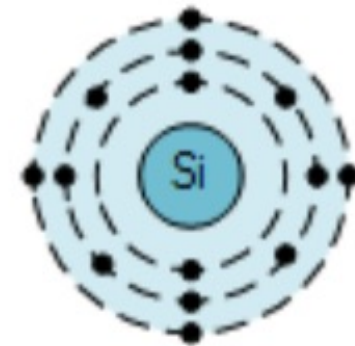
- In an ideal state, each atom will have a full outer (valence) shell;
- Atoms may give away a few electrons to expose an underlying complete shell;
- Atoms may also accept a few electrons to complete the outer shell;
- A simpler solution is to 'share' electrons among atoms.

# Silicon ( $Z = 14$ )

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2 electrons in the 1 – shell  
8 electrons in the 2 – shell  
4 electrons in the 3 – shell (valence)  
14 = Atomic number.

A Silicon Atom,  
Atomic number = "14"

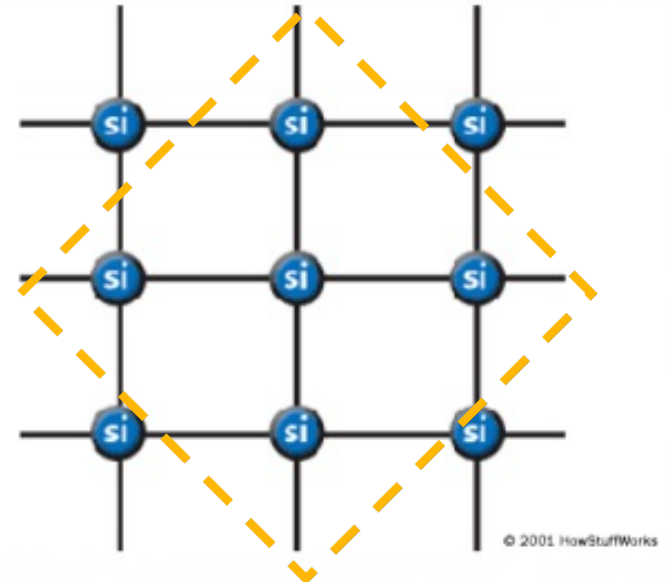


# Silicon ( $Z = 14$ )

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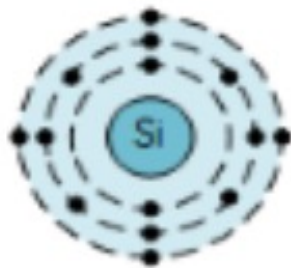
5 Silicon atoms come together to share the single electron in the valence.

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

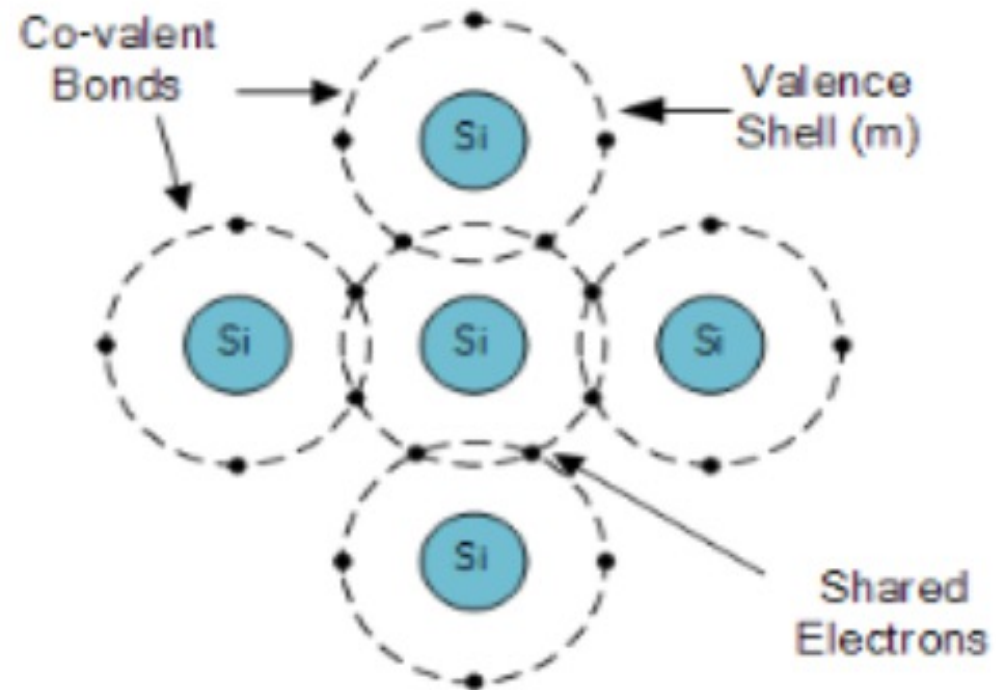


# Silicon ( $Z = 14$ )

A Silicon Atom,  
Atomic number = "14"



Silicon atom showing  
4 electrons in its outer  
valence shell (m)

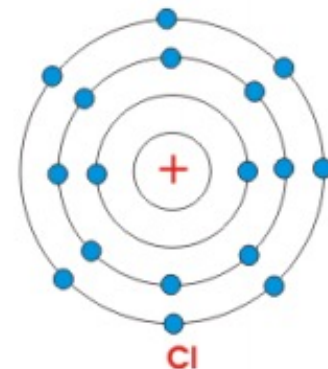
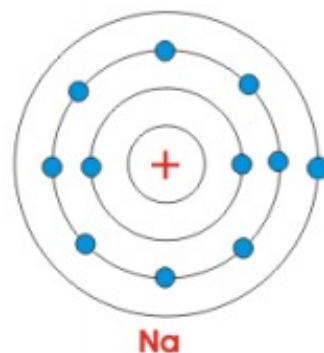


Silicon Crystal Lattice

# 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 its outer shell.
- NaCl is table salt.

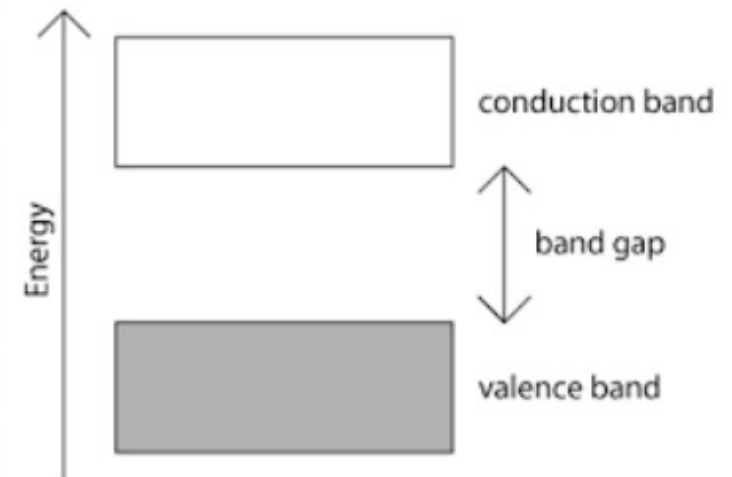




# Current in Semiconductors

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- In an unexcited (no external energy such as heat) atom, there are no electrons in the conduction band. This condition occurs only 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

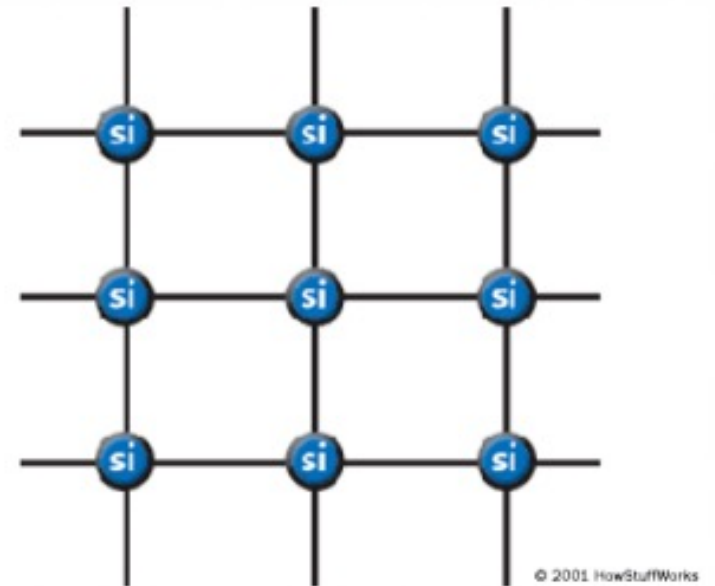
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- When a voltage is applied across a piece of intrinsic semiconductor, the previously generated free electrons in the conduction band are attracted towards the positive end -> electron current.
- Hole current moves towards the negative end.

# Intrinsic Semiconductors (Pure)

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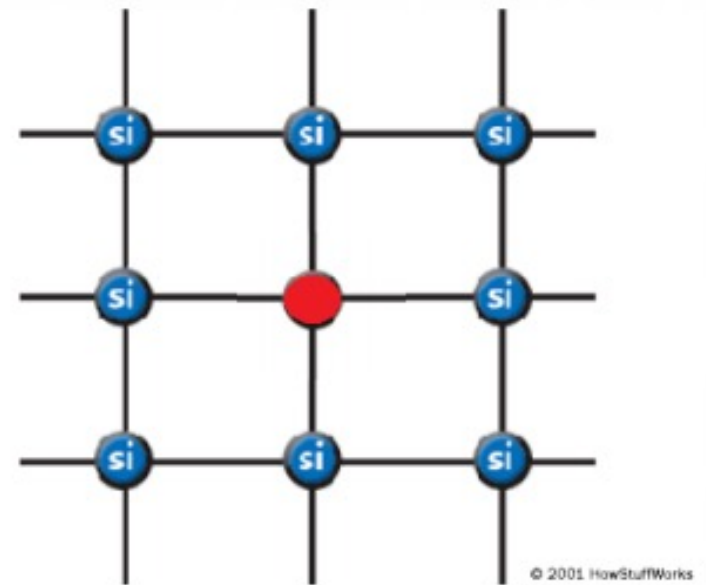
- Intrinsic semiconductors are made up of all the same atoms, i.e., silicon.
- The silicon atom has 4 electrons in the valence shell and it shares with 4 adjoining silicon atoms to fulfill its outer shell.
- This is known as **covalent bond** and it is electrically neutral.



# Extrinsic Semiconductors (Impure)

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- In order to drastically improve the conductivity of a semiconductor 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

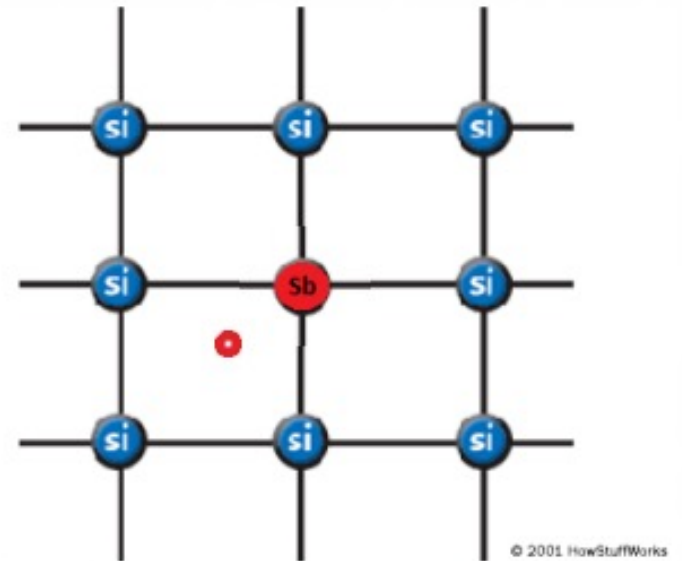
Lets start with a pure Silicon (Si)  
It has 4 electrons in it's Valence shell.

Introduce an Antimony (Sb)

This has 5 electrons in its valence shell.

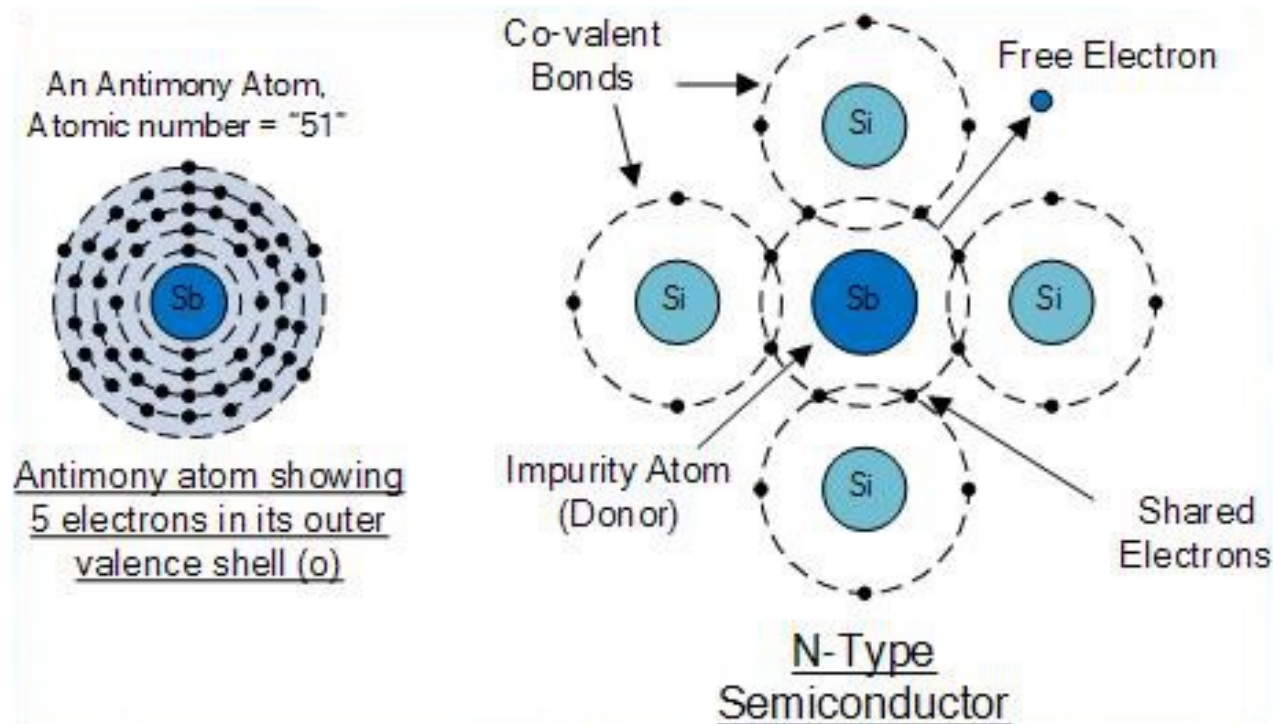
$4+5 = 9$  electrons in valence shell.

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.



# p-type Doping

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

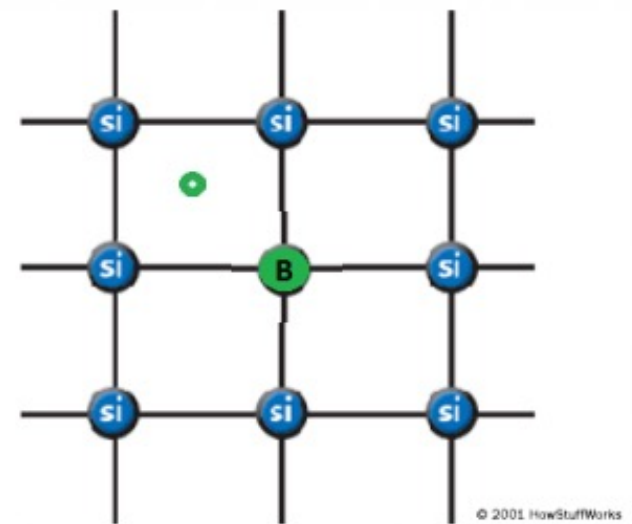
It has 4 electrons in its valence shell.

Introduce a Boron (B)

This has 3 electrons in its valence shell.

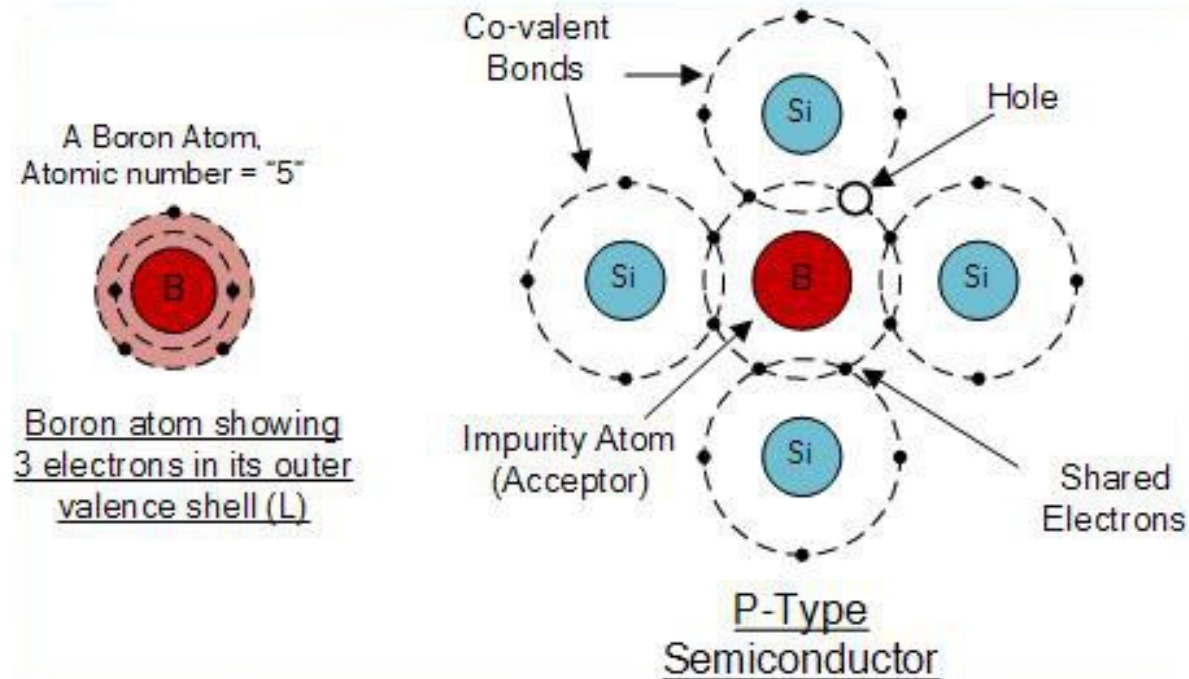
$4 + 3 = 7$  electrons in valence shell.

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).





# Some Questions for You

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- 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

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