



JOINT INSTITUTE
交大密西根学院

ECE3110J/VE311 Electronic Circuits

Introduction and Background

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Joint Institute, SJTU



Syllabus

Class: 4:00 – 5:40 pm Tuesdays and Thursdays, and 1st and 2nd weeks of Friday at 东下院 205

***Purely offline. Lectures will not be recorded.**

Office hour: Friday 9:00 am – noon at JI building 544,
or please send me an email to arrange a meeting

Labs: TBD

Piazza: <https://piazza.com/sjtu.org/fall2023/ece3110j>

JI		Mon	Tues	Wed	Thu	Fri	Sat	Sun
Fall	1	11/Sep	12	13	14	15	16	17
	2	18	19	20	21	22	23	24
	3	25	26	27	28	29	30	1/Oct
	4	2	3	4	5	6	7	8
	5	9	10	11	12	13	14	15
	6	16	17	18	19	20	21	22
	7	23	24	25	26	27	28	29
	8	30	31	1/Nov	2	3	4	5
	9	6	7	8	9	10	11	12
	10	13	14	15	16	17	18	19
	11	20	21	22	23	24	25	26
	12	27	28	29	30	1/Dec	2	3
	13	4	5	6	7	8	9	10
	14	11	12	13	14	15	16	17

Teaching members and Contacts

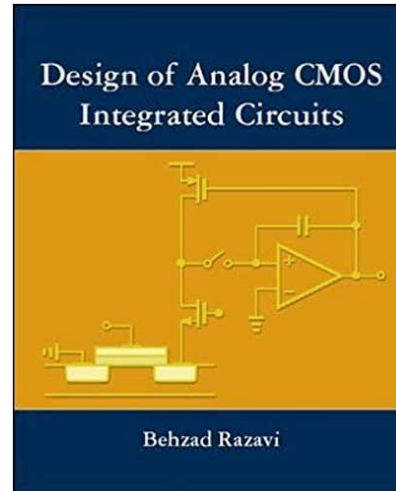
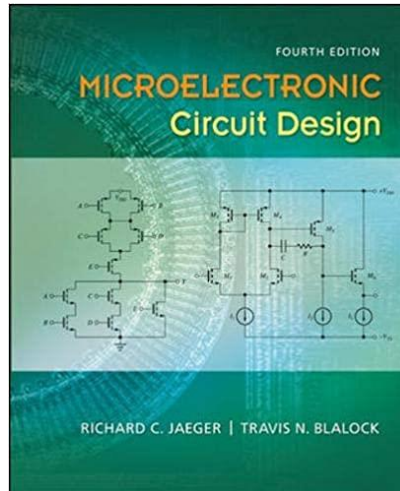
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Textbook



BEHZAD RAZAVI Fundamentals of Microelectronics



SECOND EDITION

WILEY

1. Microelectronic Circuit Design, Richard C. Jaeger, McGrawHill
2. Design of Analog CMOS Integrated Circuits, Behzad Razavi, McGrawHill
3. Fundamentals of Microelectronics, Behzad Razavi, Wiley

Grading policy

6 Homework Assignments	12 %
6 Lab Participation and Lab Reports	18 (6 + 12) %
5 Quizzes	5 %
Midterm Exam	32 %
Final Exam	33 %

Course contents

In the course VE311, we will learn working principles of nonlinear semiconductor devices and analog circuits (Amplifier) based on those devices.

1. Introduction and Solid-State Electronics
2. Diode and Diode Circuit
3. Bipolar Junction Transistor (BJT)
4. BJT Circuit
5. Basic MOS Device Physics
6. MOSFET Single Stage Amplifier
7. MOSFET Differential Amplifier
8. MOSFET Current Mirror

Feishu course group



ECE3110J Fall 2023

上海交通大学



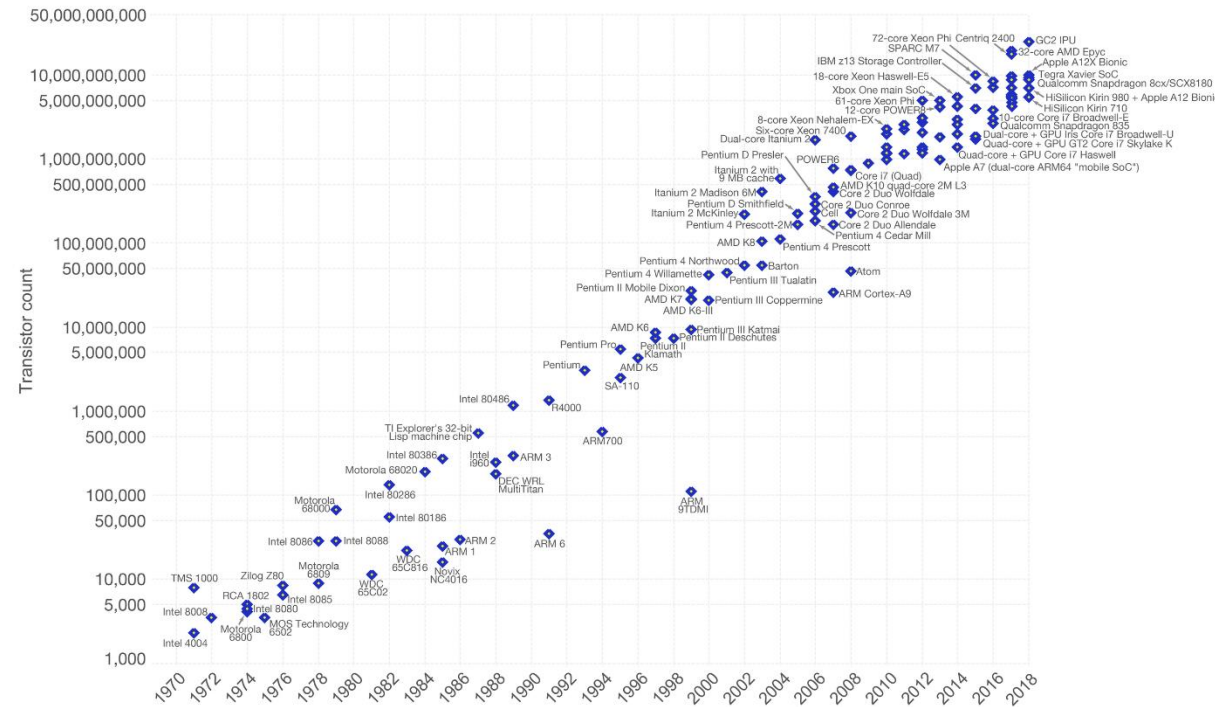
Only members of this organization can join this
group

This QR code is valid for 1 year (before 2024/8/29)

History of Electronics

Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.

Semiconductor
device
fabrication

MOSFET scaling
(process nodes)

10 μm – 1971

6 μm – 1974
2 μm – 1977

1.5 μm – 1981

1 μm – 1984

600 nm – 1999

350 nm – 1993

250 nm – 1996

180 nm – 1999

90 nm – 2003

65 nm – 2005

45 nm – 2007

22 nm = 2012

14 nm – 2014

10 nm – 2016

5 nm = 2020

Future

3 nm ~ 2023

2 nm ~ 2024

Since the commercial introduction of the integrated circuit, increases in transistors' density have been achieved through a continued reduction in **minimum feature size**. Many companies in a semiconductor industry around the world are actively working on below 3 nm processes.

Electronics

Electronics is a scientific and engineering discipline that studies and applies the principles of physics to **design, create, and operate devices** that manipulate electrons and other charged particles.

Electronics have a profound impact on various aspects of modern society and culture, such as communication, education, health care, and security. The main driving force behind the advancement of electronics is the **semiconductor industry, which produces the basic materials and components for electronic devices and circuits.**

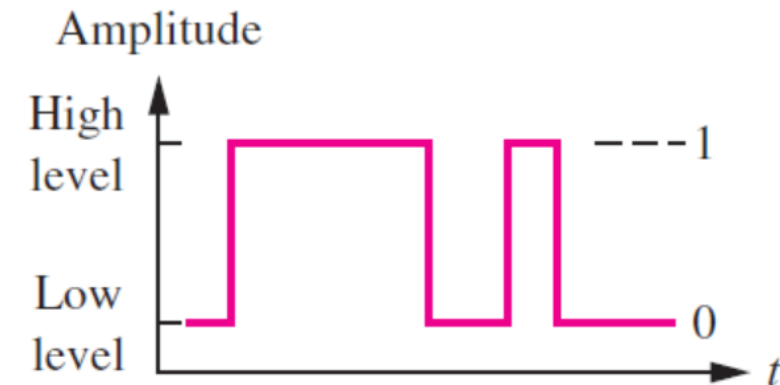
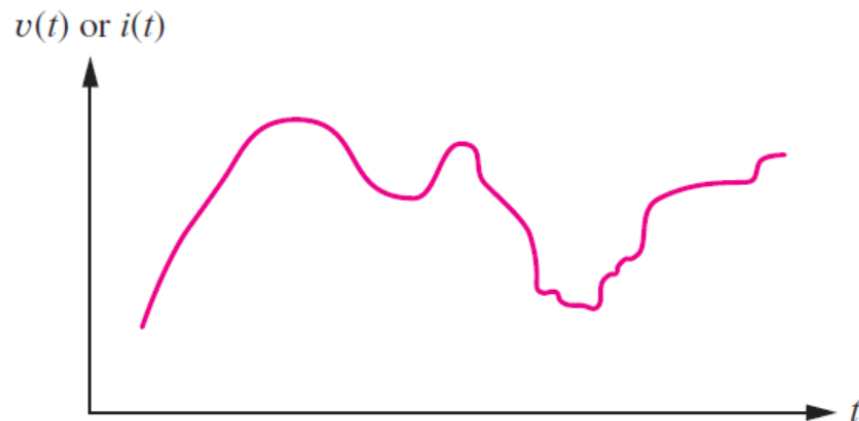
Subfields [\[edit \]](#)

- | | | |
|---------------------------------------|---------------------------------------|---|
| • Analog electronics | • Embedded systems | • Power electronics |
| • Audio electronics | • Integrated circuits | • Semiconductor devices |
| • Bioelectronics | • Microelectronics | • Telecommunications |
| • Circuit design | • Nanoelectronics | |
| • Digital electronics | • Optoelectronics | |

Classification of Electronic Signal

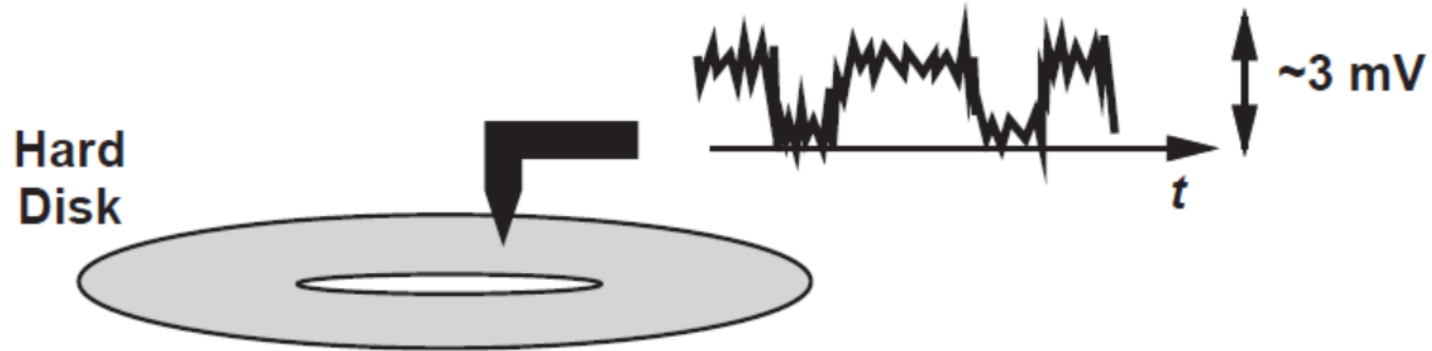
Analog signals: A continuous range of values representing continuously varying quantities

Digital signals: A signal that represents data as a sequence of discrete values



When we speak of digital electronics, we are most often referring to electronic processing of **binary digital signals**, or signals that can take on only one of two discrete amplitude levels

Digital signal in reality



Many digital binary signals must be viewed and processed as analog waveforms.

e.g. Information stored on a hard disk in a computer, upon retrieval, the “digital” data appears as a **distorted waveform with only a few millivolts of amplitude**. Such a small separation between ONES and ZEROS proves inadequate if this signal is to drive a logical gate, demanding **a great deal of amplification and other analog processing** before the data reaches a robust digital form.

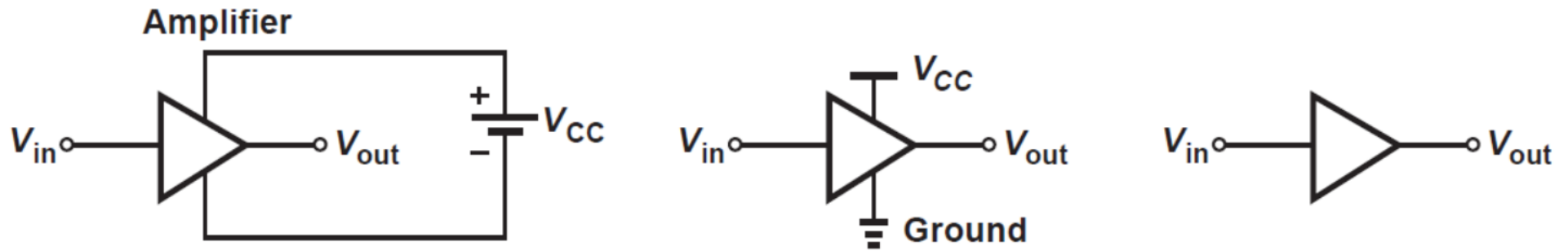
Amplifier

The most commonly-used analog function is amplification. An amplifier is necessary to raise the signal swing to acceptable levels. The performance of an amplifier is characterized by a number of parameters, e.g., **gain**, speed, and power dissipation. **We study these aspects of amplification in great detail.**

A voltage amplifier produces **an output swing greater than the input swing**. The voltage gain, A_v , is defined as

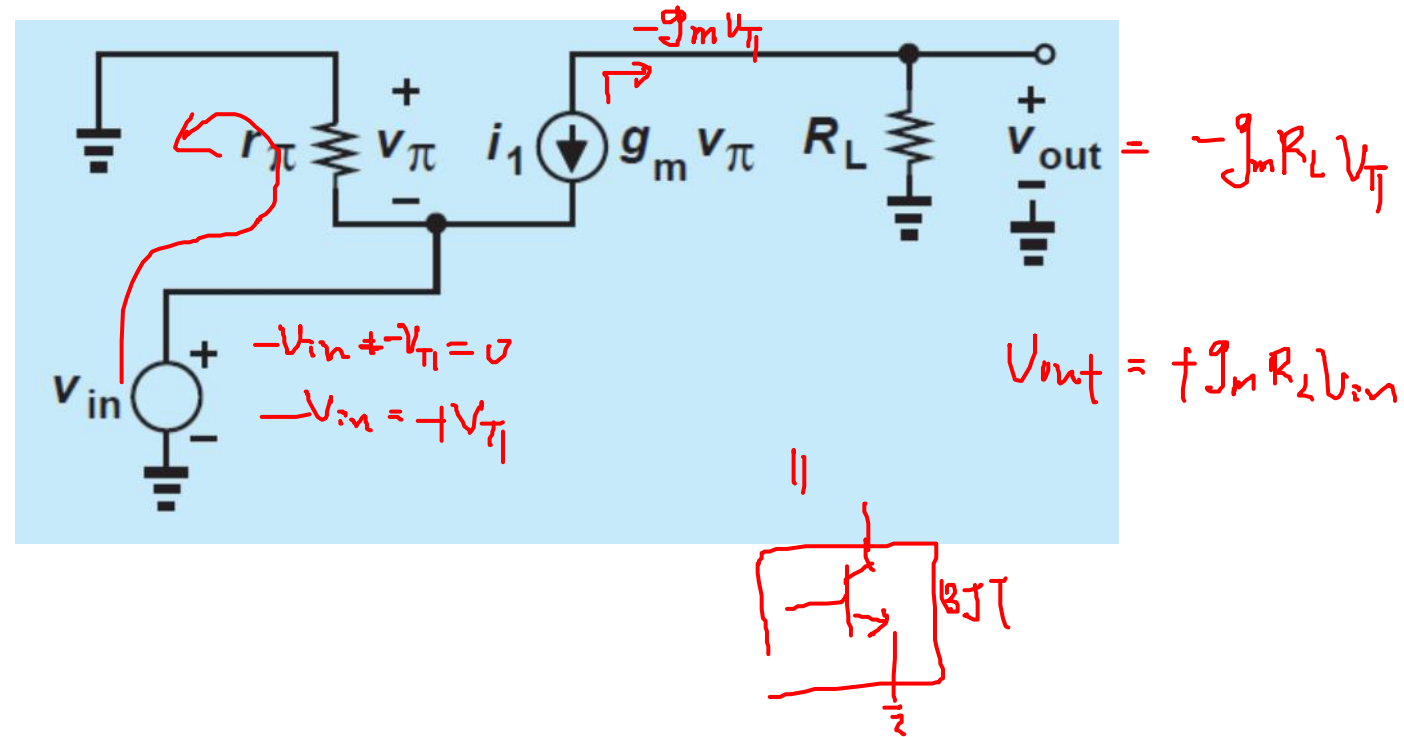
$$A_v = \frac{v_{out}}{v_{in}}, \text{ or } A_{v|dB} = 20 \log \frac{v_{out}}{v_{in}}$$

Circuit Drawing



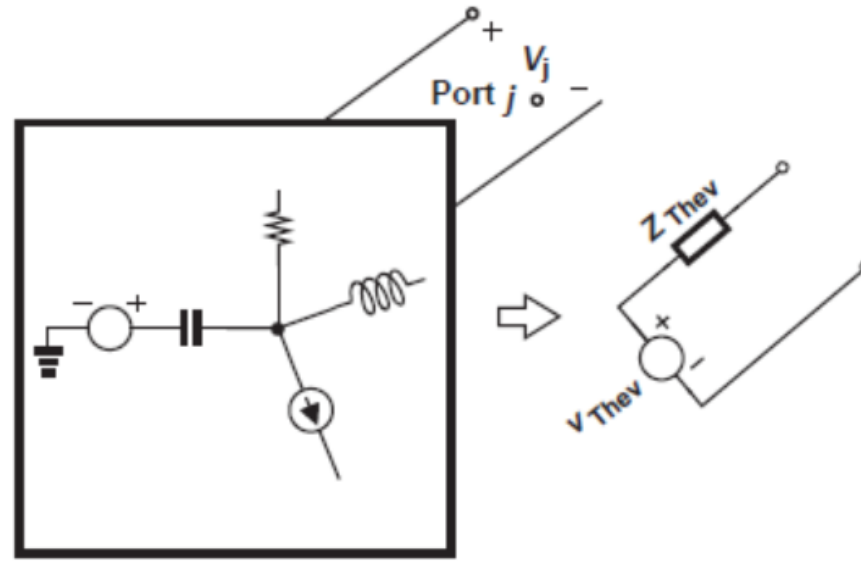
In order to operate properly and provide gain, **an amplifier must draw power from a voltage source**. This source is typically denoted by V_{CC} or V_{DD} . In complex circuits, we may simplify the notation to that shown in the figure above. Typical amplifiers operate with supply voltages in the range of 1 V to 10 V.

Voltage gain A_v for the circuit below, for example,



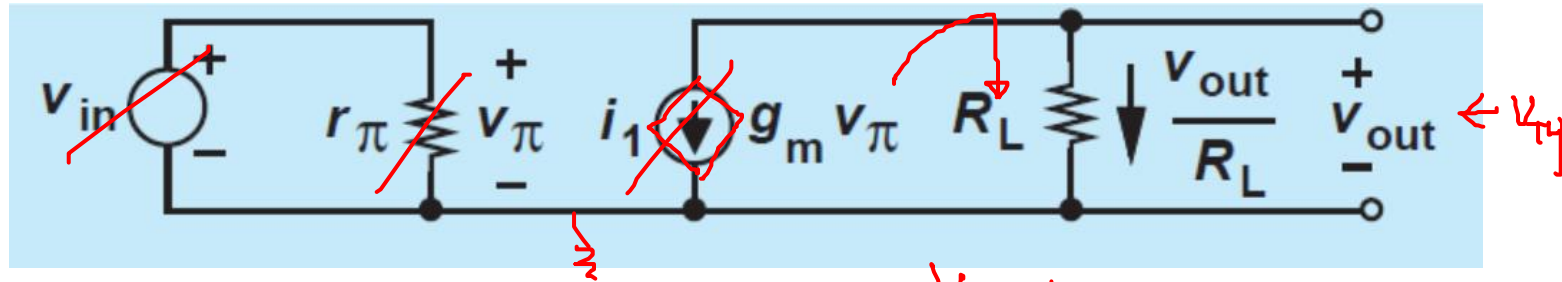
As we see above, there are knowledges that we are going to learn to analyze electronic circuits. However, basic laws that we learned in VE215 will also be frequently used. **Don't be afraid of VE311 too much.**

Thevenin Equivalent Circuit



Thevenin's theorem states that a **(linear) one-port network** can be replaced with an **equivalent circuit** consisting of **one voltage source** in series with **one impedance**.

e.g. Determine the Thevenin equivalent circuit of the circuit below

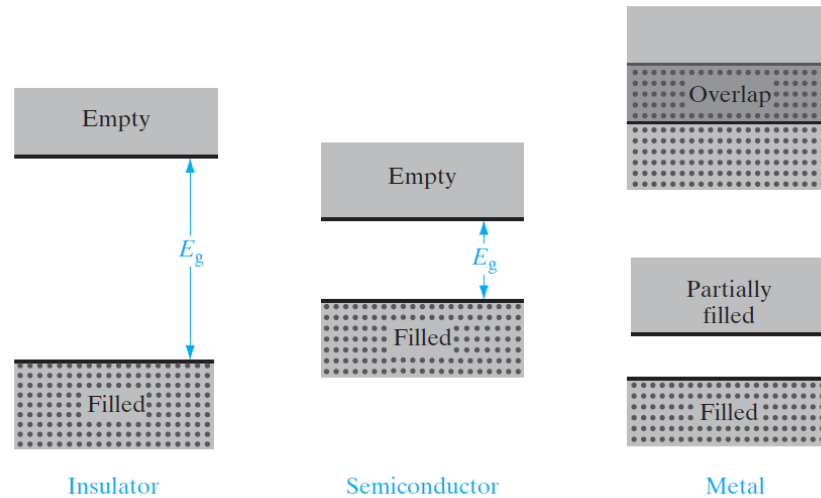


$$V_T = v_{out} = -g_m R_L V_\pi$$

$$V_{in} = V_\pi$$

$$R_{eq} = R_L$$

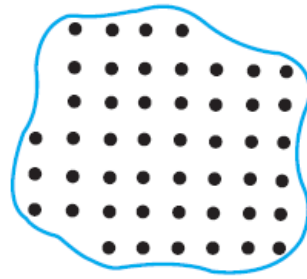
Solids and Semiconductor



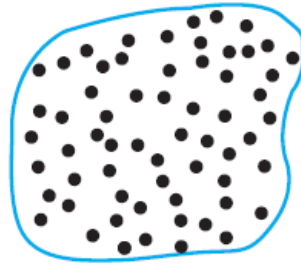
(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te
(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds	
	Si	SiC	AlP	ZnS	
	Ge	SiGe	AlAs	ZnSe	
			AlSb	ZnTe	
			GaN	CdS	
			GaP	CdSe	
			GaAs	CdTe	
			GaSb		
			InP		
			InAs		
			InSb		

The atoms in a semiconductor are **materials from either group IV** of the periodic table (elemental semiconductor), or from **a combination of group III and V**, or group II and VI (compound semiconductor). Because different semiconductors are made up of elements from different groups in the periodic table, properties vary between semiconductors.

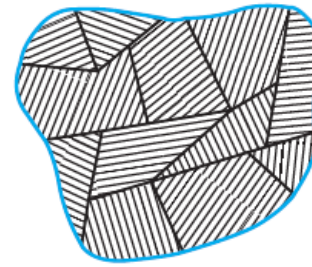
Crystals of Solids



(a) Crystalline



(b) Amorphous



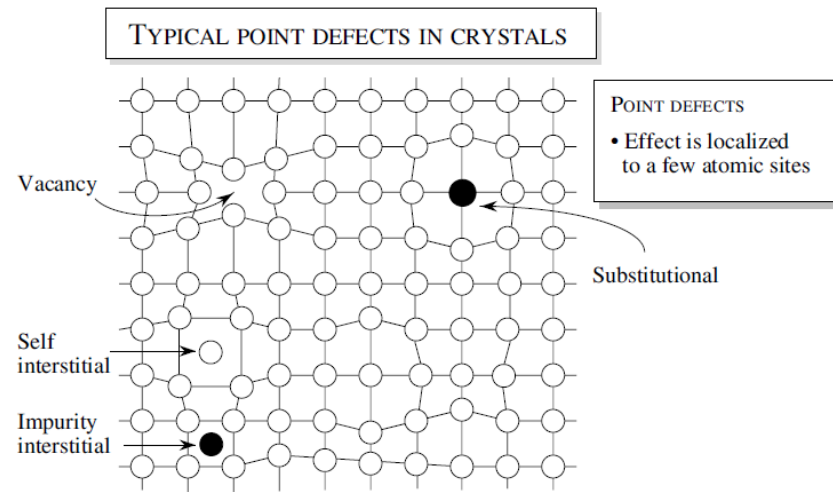
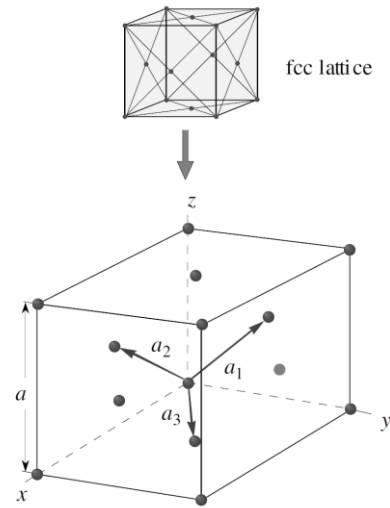
(c) Polycrystalline

Crystalline solid: atoms making up the crystal are arranged in a periodic fashion

Amorphous solid: no periodic structure at all

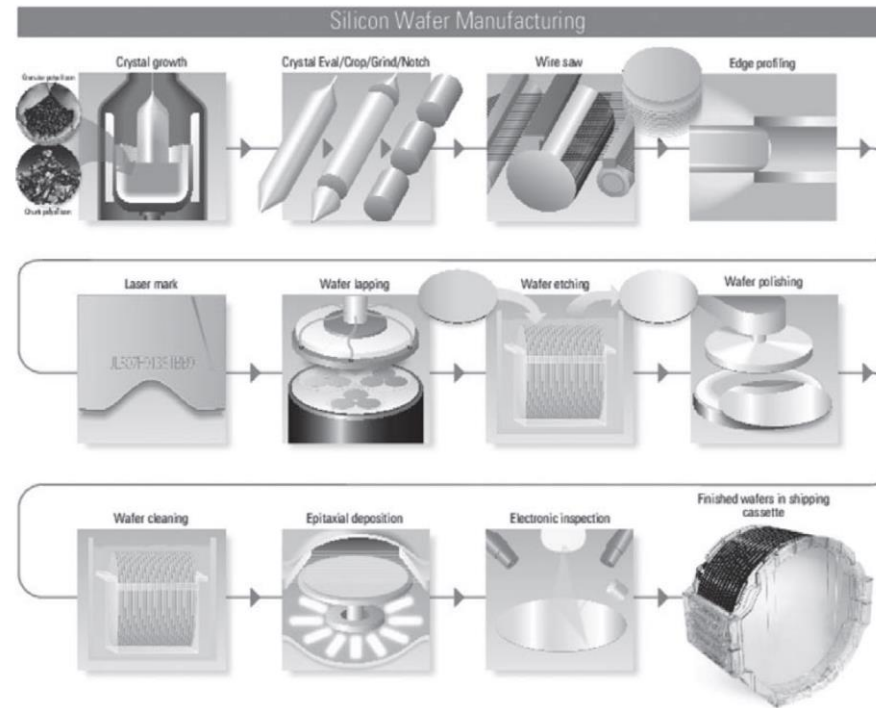
Polycrystalline solid: many small regions of single-crystal material

Semiconductor devices are based on **crystalline materials**. e.g. Silicon (Si) has a diamond structure with a fcc lattice. These collective crystal structure form solid and decides **electronics levels of materials**.



Semiconductor structures can operate at their potential only if they can be grown with a **high degree of crystallinity** and if **impurities and defects can be controlled**.

Si wafers for IC chips



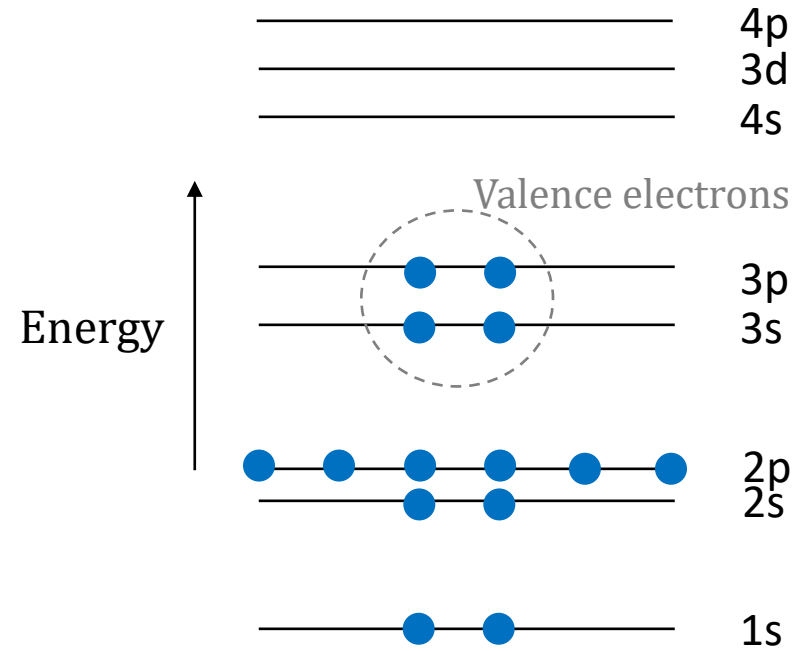
The progress of solid state device technology since the invention of the transistor in 1948 has depended **not only on the development of device concepts but also on the improvement of materials.** The requirements on the growing of device-grade semiconductor crystals are more stringent than those for any other materials.

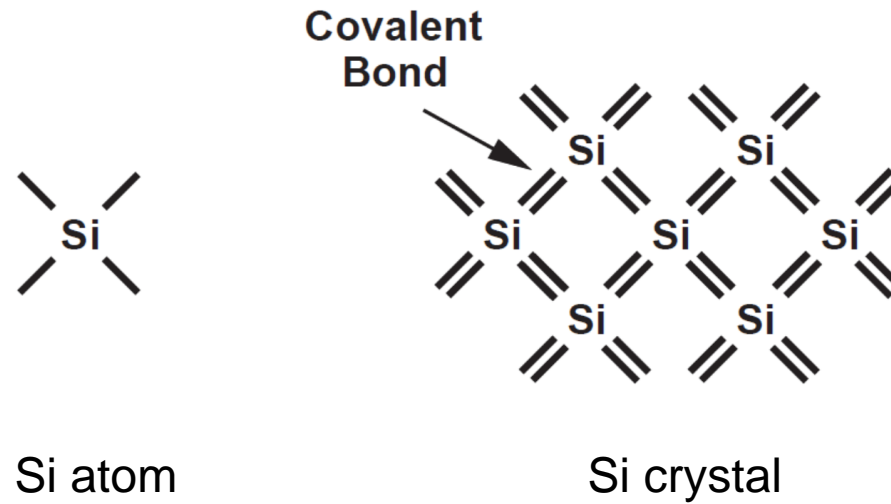


Covalent Bond Model

Atoms can bond together in amorphous, polycrystalline, or single-crystal forms. Most of the useful properties of semiconductors occur **in high-purity, single-crystal material**.

The atom's chemical activity is determined by the electrons in the outermost shell, valence electrons, and how complete this shell is.

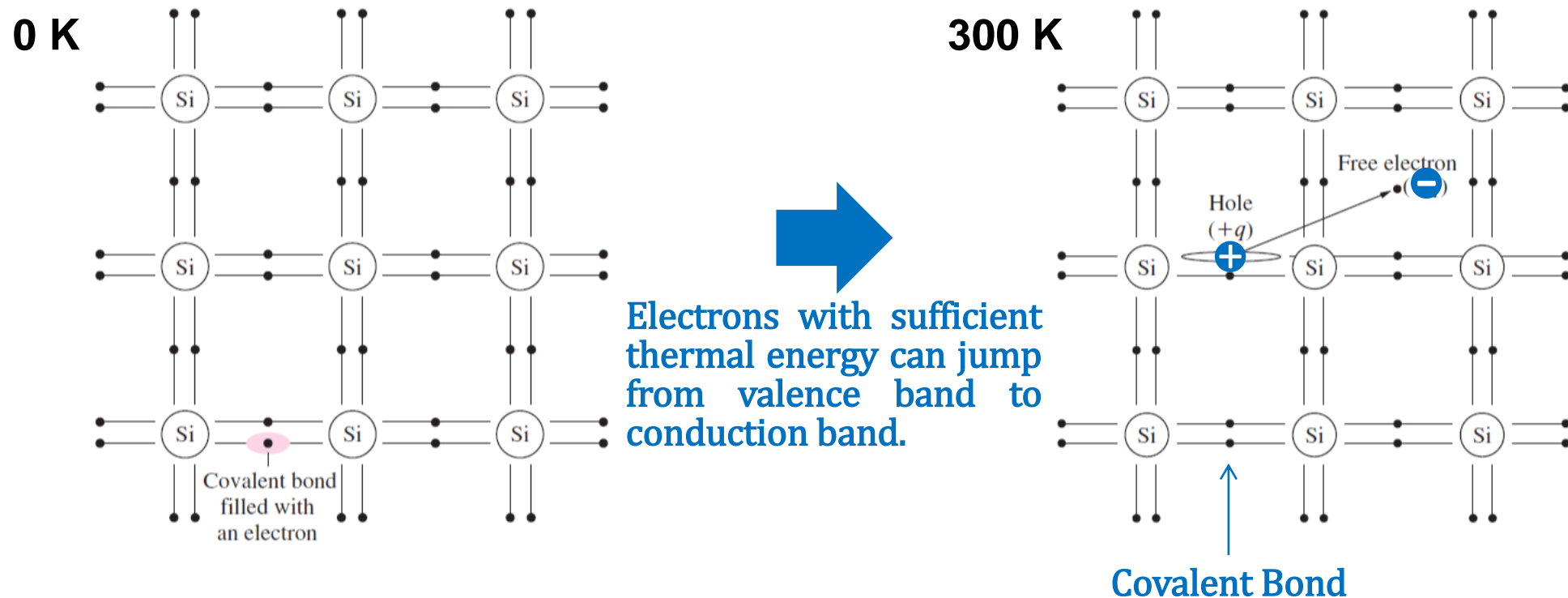




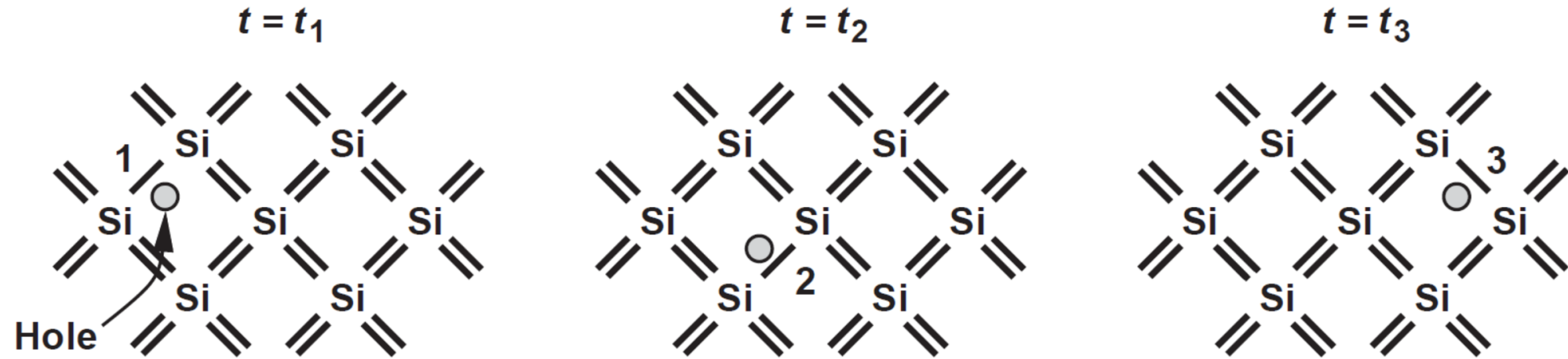
For example, Silicon (Si) has four electrons in the outer shell. Single-crystal material is formed by **the covalent bonding of each silicon atom** with its four nearest neighbors in a highly regular three-dimensional array of atoms.

At 0 K, all the electrons reside in the covalent bonds are shared between the atoms in the array, with no electrons free for conduction. The outer shells of the silicon atoms are full, and the material **behaves as an insulator**.

As the temperature increases, **thermal energy** is added to the crystal and some **bonds break, freeing a small number of electrons for conduction**.



Holes



When freed from a covalent bond, an electron leaves a **void** behind because the bond is now incomplete. **Called a hole**, such a void can readily absorb a free electron if one becomes available. Thus, we say **an electron-hole pair** is generated when an electron is freed, and an **electron-hole recombination** occurs when an electron falls into a hole.

Bandgap energy E_g is the minimum energy needed to **break a covalent bond** in the semiconductor crystal, thus **freeing electrons for conduction**. e.g. **Silicon, the material for modern electronics**, has a bandgap of 1.12 eV.

TABLE 2.3

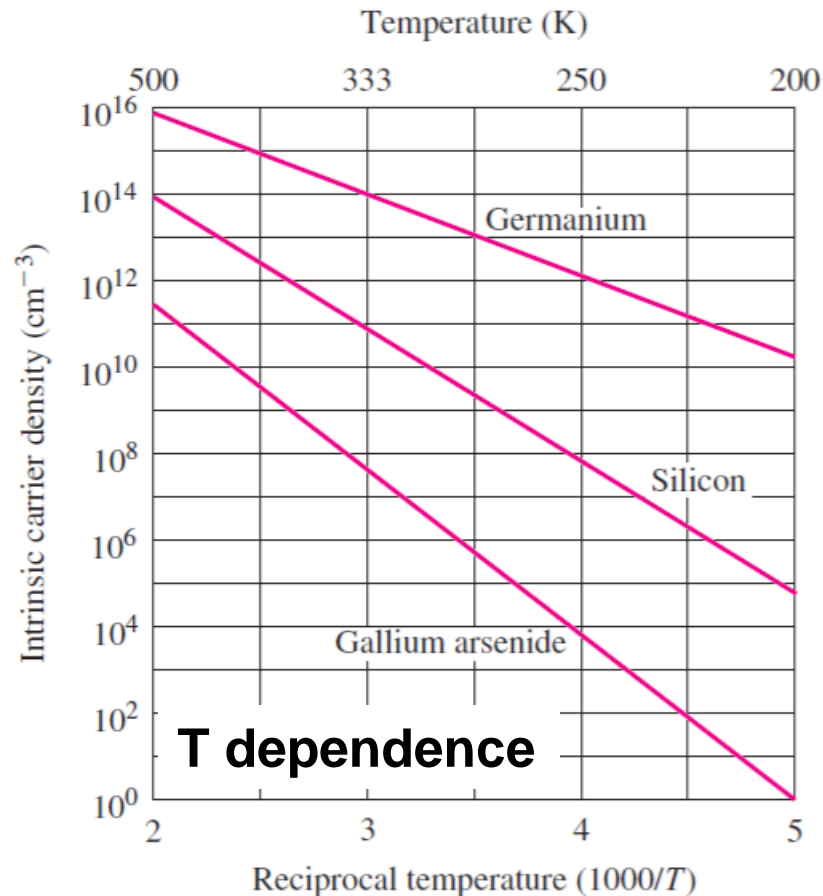
Semiconductor Materials

SEMICONDUCTOR	BANDGAP ENERGY E_g (eV)
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Silicon germanium	1.10
Cadmium selenide	1.70

Intrinsic Carrier Density

$$n = p = n_i$$

The density of conduction (or free) electrons is represented by the symbol **n (electrons/cm³)**, and for **intrinsic material** **n = n_i**. The term intrinsic refers to the generic properties of pure material.



$$n_i^2 = BT^3 \exp\left(-\frac{E_g}{kT}\right) [cm^{-6}]$$

k = Boltzmann's constant, 8.62×10^{-5} eV/K

B = material-dependent parameter

e.g. Si = 1.08×10^{31} [K⁻³/cm⁻⁶]

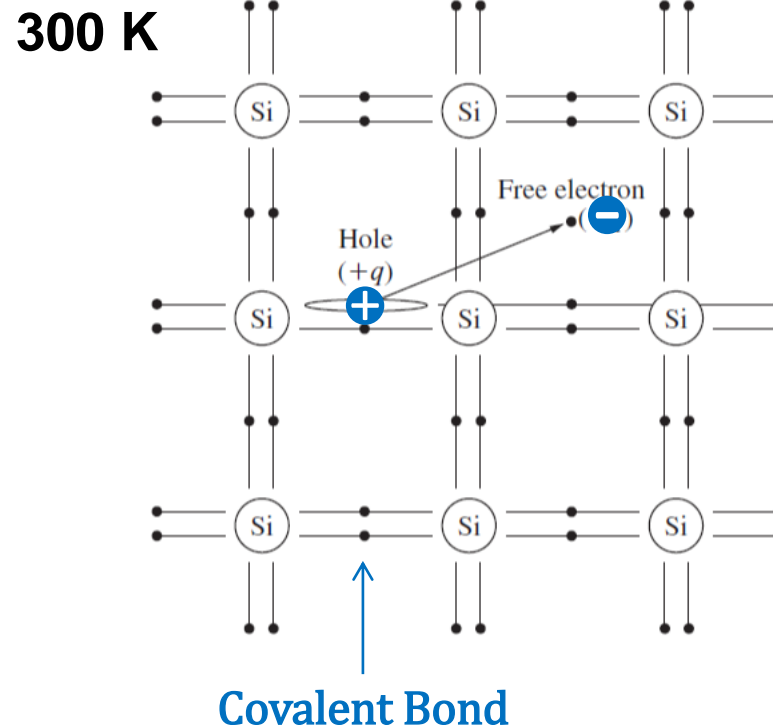
At 300 K n_i of Si is

$$n_i^2$$

$$= (1.08 \times 10^{31}) 300^3 e^{\frac{-1.12}{(8.62 \times 10^{-5}) \times 300}}$$

$$= 4.52 \times 10^{19} (1/cm^6)$$

$$n_i = 6.73 \times 10^9 (1/cm^3) \cong 10^{10} (1/cm^3)$$

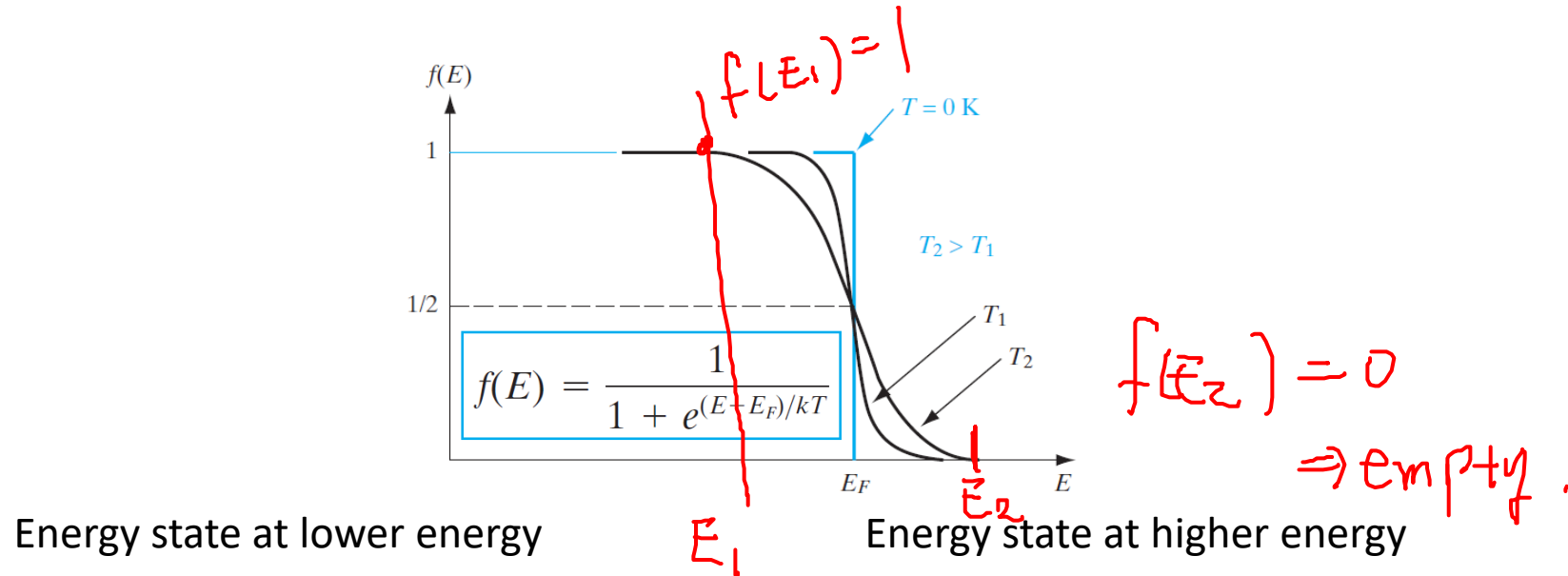


$$n = p = n_i$$

$$np = n_i^2$$

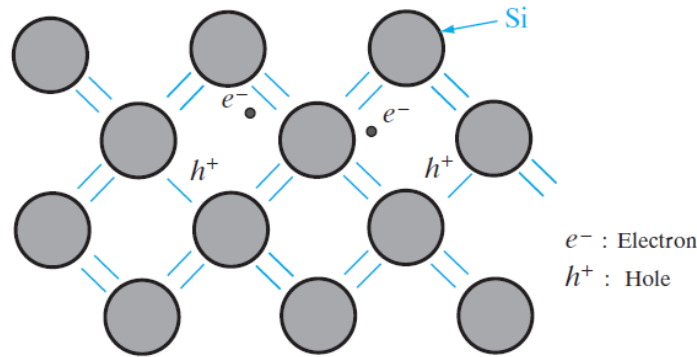
When the covalent bond is broken an electron moves away from the covalent bond. It leaves behind a **vacancy**. The vacancy is left with an effective charge of $+q$, called a **hole**. Hole density is represented by the symbol p (holes/cm³). For intrinsic silicon, $n = n_i = p$, and thus $pn = n_i^2$ at thermal equilibrium.

Fermi–Dirac distribution function

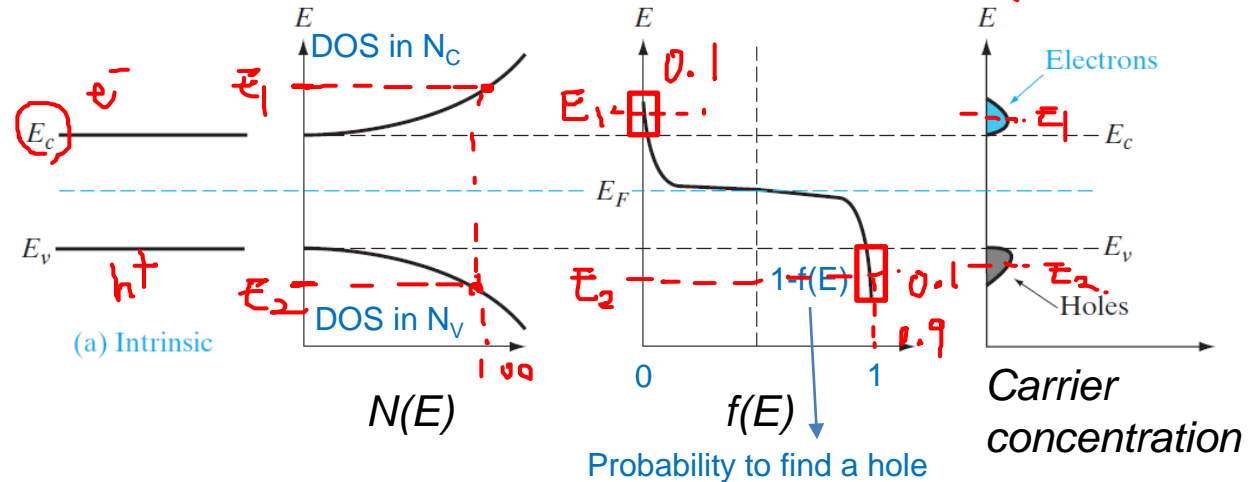


The function $f(E)$, the *Fermi–Dirac distribution function*, gives the **probability that an available energy state at E will be occupied by an electron** at absolute temperature T . The quantity E_F is called the **Fermi level**. We notice that, for an energy E equal to the Fermi level energy E_F , the occupation probability is $1/2$.

Intrinsic material



e^- : Electron
 h^+ : Hole



* of e^- at $E_1 = 10$
* of h^+ at $E_2 = 10$

Density of States $N(E)$

of states / ($\text{cm}^3 \cdot \text{J}$)

Fermi-Dirac Distribution $f(E)$

(the probability of the state occupied with an electron)

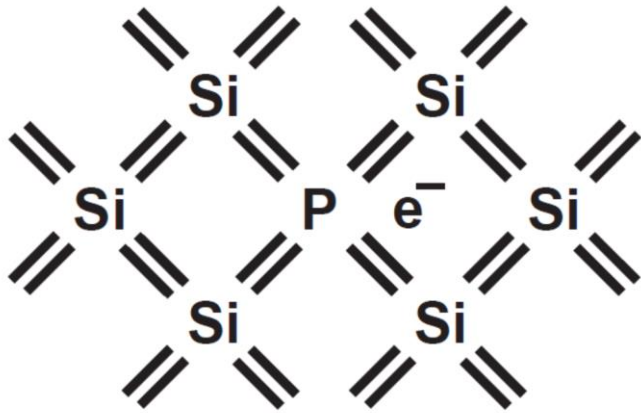
$$f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}$$

$$n = \int_{E_c}^{\infty} f(E) N(E) dE = n_i$$

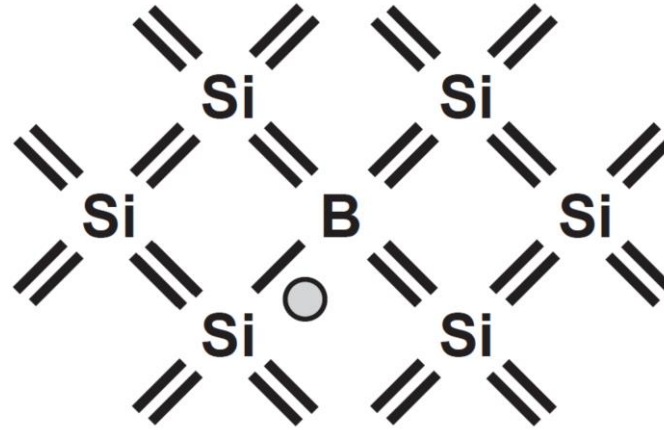
$$p = \int_{-\infty}^{E_v} [1 - f(E)] N(E) dE = n_i \quad (1 / \text{cm}^3)$$

$$n = p = n_i$$

Electron and Hole Concentrations in Doped Semiconductors



As phosphorus (P) contains five valence electrons each P atom shares four electrons with the neighboring silicon atoms, leaving the fifth electron unattached. **This electron is free to move, serving as a charge carrier.** The controlled **addition of an impurity** such as phosphorus to an intrinsic semiconductor is called **doping**, and phosphorus itself a **dopant**. The doped silicon crystal is now called **extrinsic or an *n*-type semiconductor**.

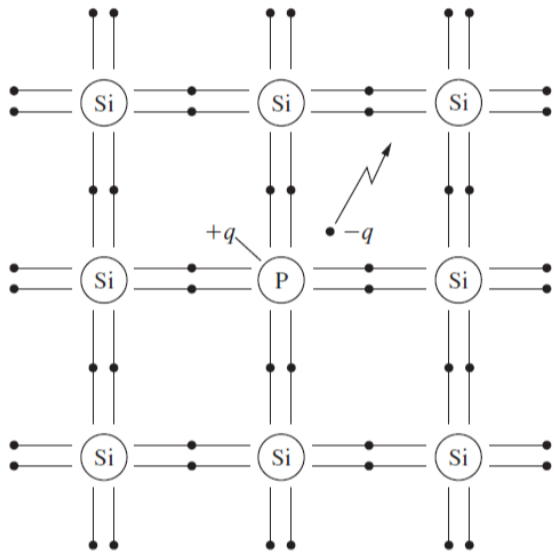


If we dope silicon with **an atom that provides an insufficient number of electrons**, then we can obtain many incomplete covalent bonds. **A boron (B) atom** can form only three complete covalent bonds in a silicon crystal. The structure above therefore exemplifies a **p-type semiconductor**, providing holes as majority carriers. The boron atom is called an **acceptor dopant**.

In doped material, the electron and hole concentrations are no longer equal.

If $n > p$, the material is called ***n*-type** where a majority carrier is electron.

If $p > n$, the material is referred to as ***p*-type** where a majority carrier is hole.



(p)

N_d = donor impurity concentration atoms/cm³

N_a = acceptor impurity concentration atoms/cm³

(B)

* Most of cases, we assume that dopants are 100% ionized.

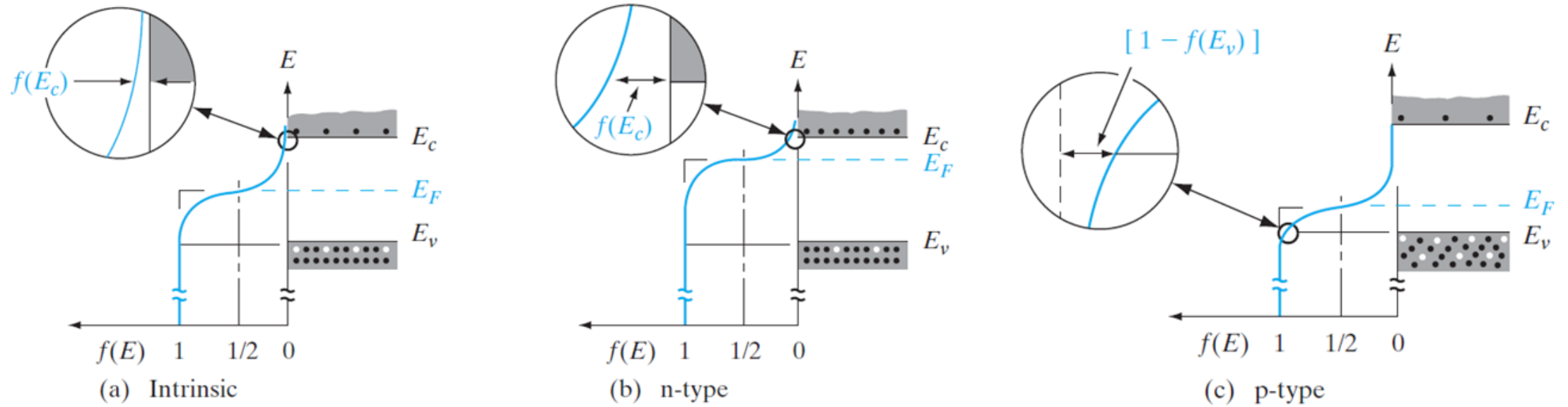
$$np = n_i^2$$

① $N_d = n$ in n -type

② $N_a = p$ in p -type

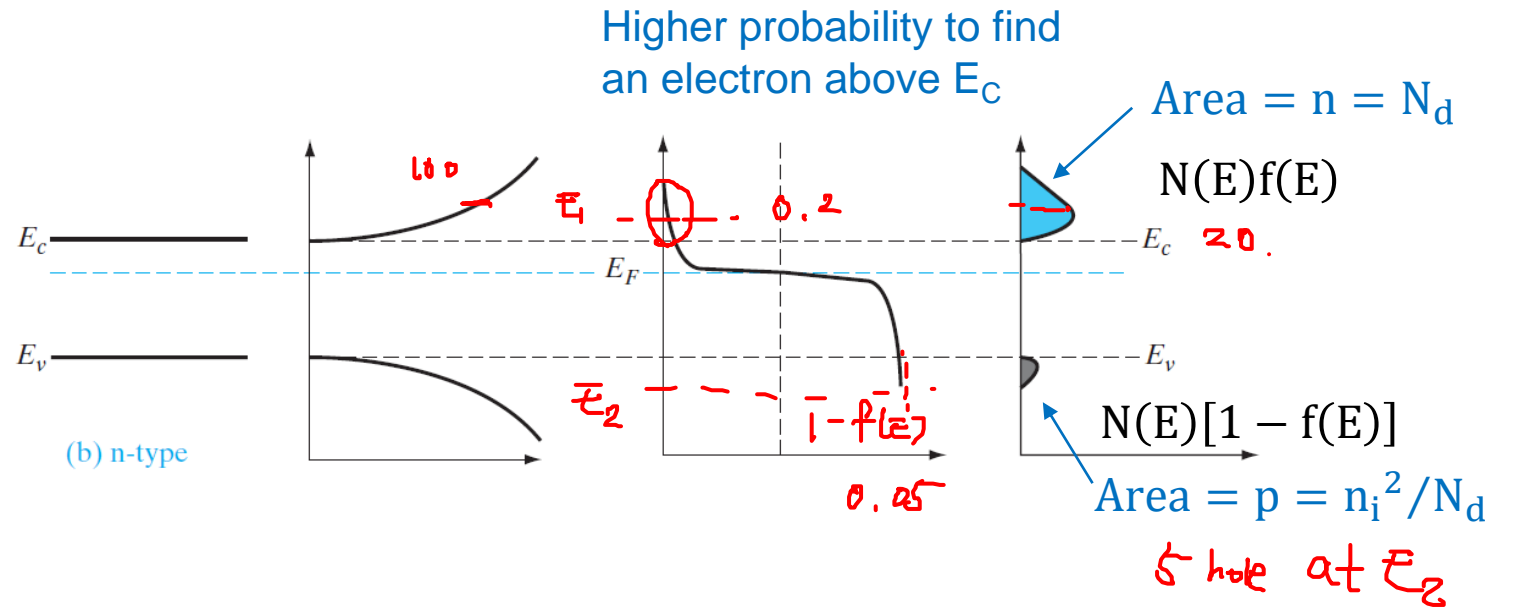
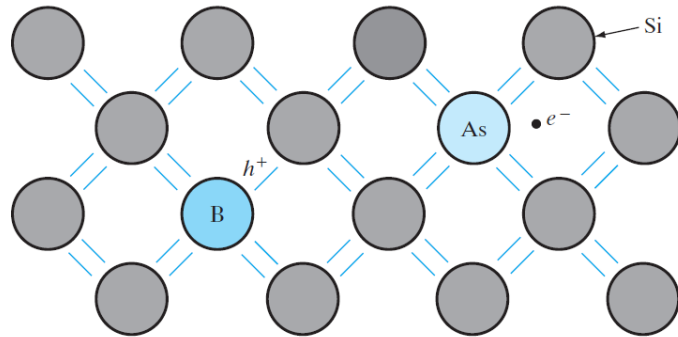
If the n-type dopant concentration $N_d \gg n_i$, $n = N_d$ and $p = n_i^2 / N_d$ (1 / cm³)

Similarly, if the p-type dopant concentration $N_a \gg n_i$, $p = N_a$ and $n = n_i^2 / N_a$ (1 / cm³)



In an **n-type**, there is a higher probability of **occupied electrons near E_c** compared to intrinsic. Similarly, in a **p-type**, there is a higher probability of **occupied holes near E_v** .

n-type material



Density of States $N(E)$
of states / ($\text{cm}^3 \cdot \text{J}$)

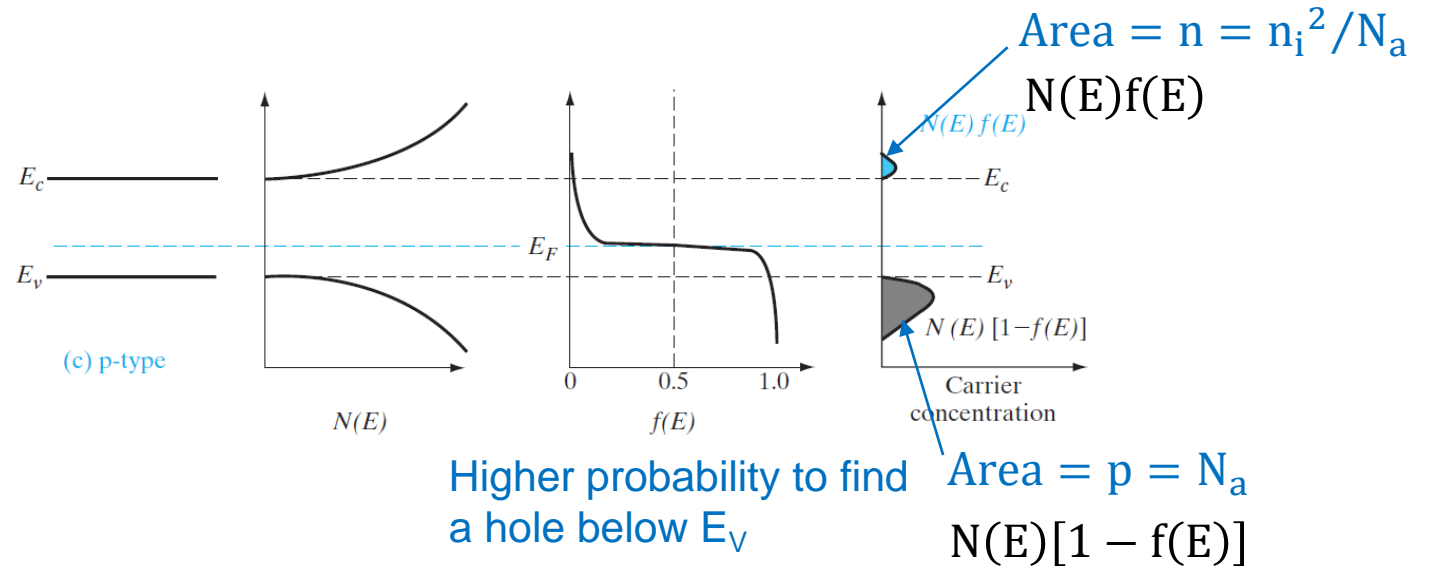
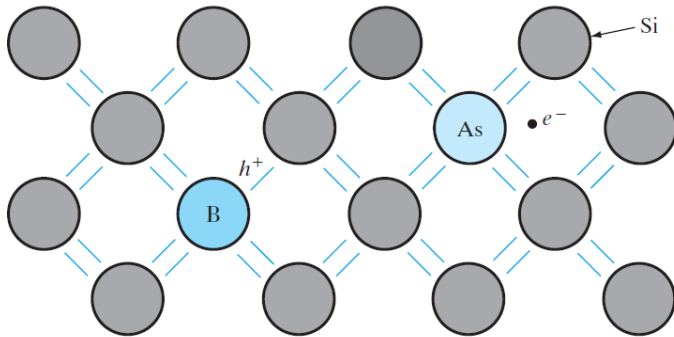
Fermi-Dirac Distribution $f(E)$
(the probability of the state occupied with an electron)

$$f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}$$

$$n = \int_{E_c}^{\infty} f(E) N(E) dE = n_i e^{\frac{E_f - E_i}{kT}} \quad (1 / \text{cm}^3)$$

$$p = \int_{-\infty}^{E_v} [1 - f(E)] N(E) dE = n_i e^{\frac{E_i - E_f}{kT}} \quad (1 / \text{cm}^3)$$

p-type material



Density of States $N(E)$
of states / ($\text{cm}^3 \cdot \text{J}$)

Fermi-Dirac Distribution $f(E)$
(the probability of the state occupied with an electron)

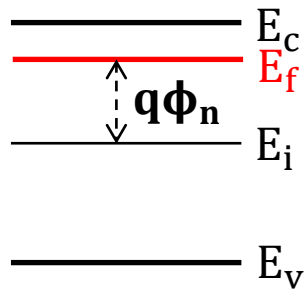
$$f(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1}$$

$$n = \int_{E_c}^{\infty} f(E) N(E) dE = n_i e^{\frac{E_f - E_i}{kT}} \quad (1 / \text{cm}^3)$$

$$p = \int_{-\infty}^{E_v} [1 - f(E)] N(E) dE = n_i e^{\frac{E_i - E_f}{kT}} \quad (1 / \text{cm}^3)$$

Energy Band of n-type and p-type Semiconductor

n-type

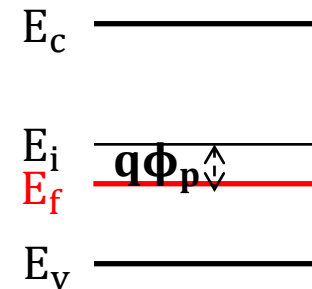


$$n = N_d = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{q\phi_n}{kT}}$$

$$p = \frac{n_i^2}{N_d} = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{-q\phi_n}{kT}}$$

$$np = n_i^2$$

p-type



$$p = N_a = n_i e^{\frac{E_i - E_f}{kT}} = n_i e^{\frac{q\phi_p}{kT}}$$

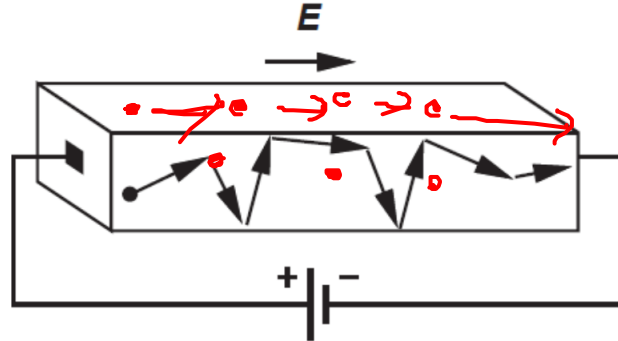
$$n = \frac{n_i^2}{N_a} = n_i e^{\frac{E_f - E_i}{kT}} = n_i e^{\frac{-q\phi_p}{kT}}$$

$$np = n_i^2$$

Currents in Semiconductors

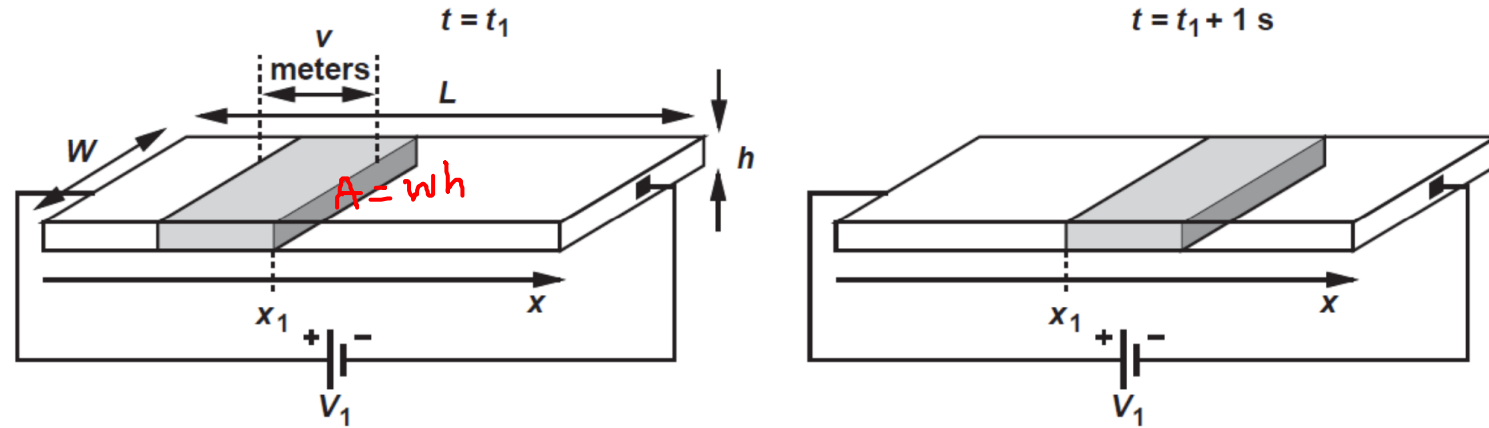
There are two kinds of currents in semiconductors: **Drift and Diffusion currents.**

(1) Drift: Movement of charge carriers due to an electric field is called drift.



The charge carriers are accelerated by the field and accidentally collide with the atoms in the crystal, eventually reaching the other end. The acceleration due to the field and the collision with the crystal counteract, leading to a **constant velocity** for the carriers.

$$\begin{aligned}\vec{v}_e &= -\mu_n \vec{E} \\ \vec{v}_h &= \mu_p \vec{E}\end{aligned}$$



Drift Current: Charged particles move or drift **in response to the electric field**, and the resulting current is called **drift current**. Assuming the electrons move with a velocity of v m/s, the current is equal to the total charge enclosed in v meters of the bar's length. Thus, drift current $I = -v \cdot \cancel{W} \cdot \cancel{h} \cdot n \cdot q$, or $J = -v \cdot n \cdot q$.

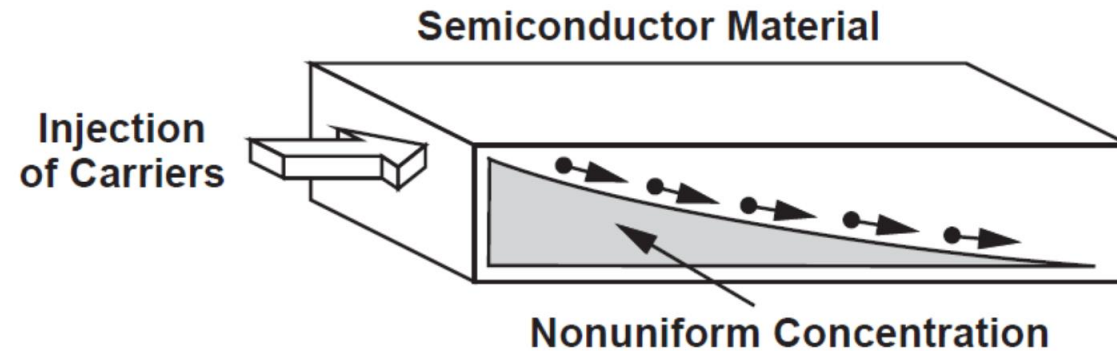
As $v_n = -\mu_n E$ and $v_p = \mu_p E$,

The total drift current density:

$$\begin{aligned} j^{drift} \text{ A/cm}^2 &= j_n^{drift} + j_p^{drift} = (-qn)(-\mu_n E) + (+qp)(+\mu_p E) \\ &= q(n\mu_n + p\mu_p)E = \sigma E \text{ where } \sigma \text{ is an electric conductivity.} \end{aligned}$$

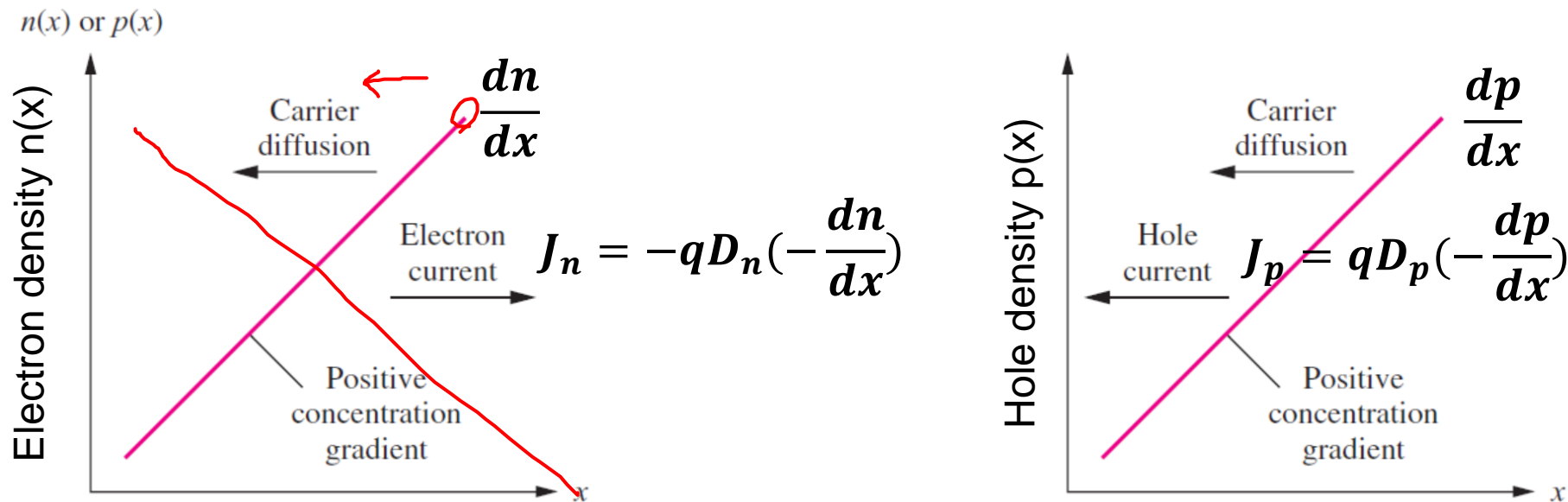
There are two kinds of currents in semiconductors: **Drift and Diffusion currents.**

(2) Diffusion: If there is a *nonuniform* density in charge carriers the carriers move toward regions of low concentration, thereby carrying an electric current even in the absence of an electric field,



Gradient of charge carrier concentration $\frac{dn}{dx}$

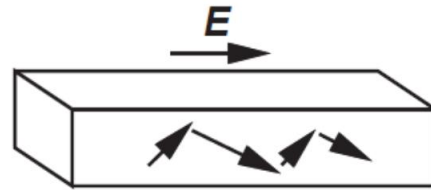
Diffusion current: Gradients in free carrier densities give rise to a current flow mechanism, called **diffusion**, i.e. **from regions of high concentration to regions of low concentration**.



$$j^{diff} A/cm^2 = j_n^{diff} + j_p^{diff} = (-q)D_n \left(-\frac{\partial n}{\partial x} \right) + (+q)D_p \left(-\frac{\partial p}{\partial x} \right)$$

where D_n is diffusion constant

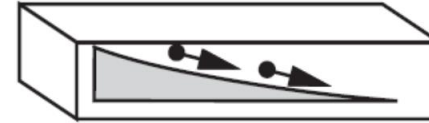
Drift Current



$$J_n = q n \mu_n E$$

$$J_p = q p \mu_p E$$

Diffusion Current



$$J_n = q D_n \frac{dn}{dx}$$

$$J_p = -q D_p \frac{dp}{dx}$$

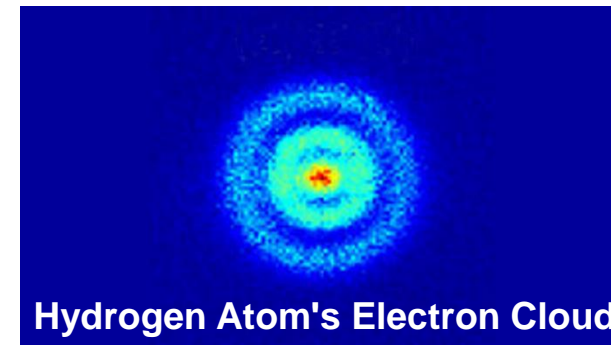
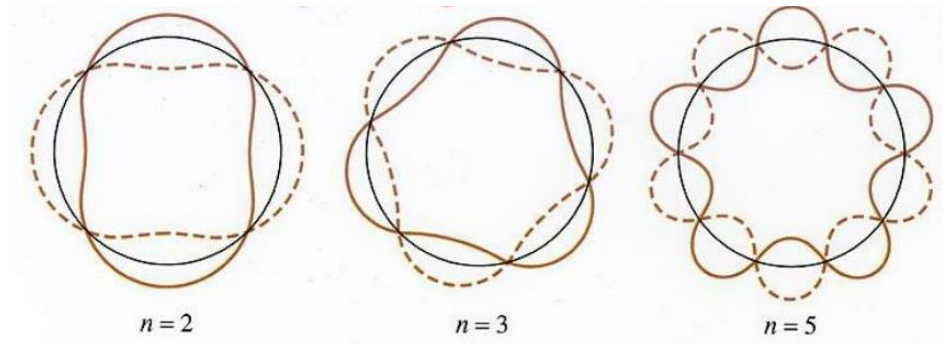
Finally, **the total current** in a semiconductor are the combination of the drift and diffusion currents.

$$j_n^{Total} = q n \mu_n E + q D_n \frac{\partial n}{\partial x}$$

$$j_p^{Total} = q p \mu_p E - q D_p \frac{\partial p}{\partial x}$$

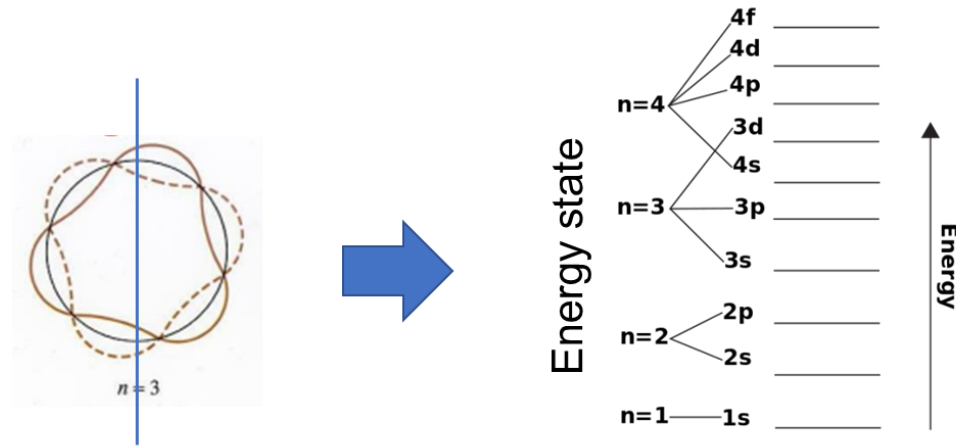
Band Theory

Quantum mechanics predicts that the highly regular crystalline structure of a semiconductor produces **periodic quantized ranges of allowed and disallowed energy states** for the electrons surrounding the atoms in the crystal.



Only integer number of wavelengths (energy state) around orbit is allowed.

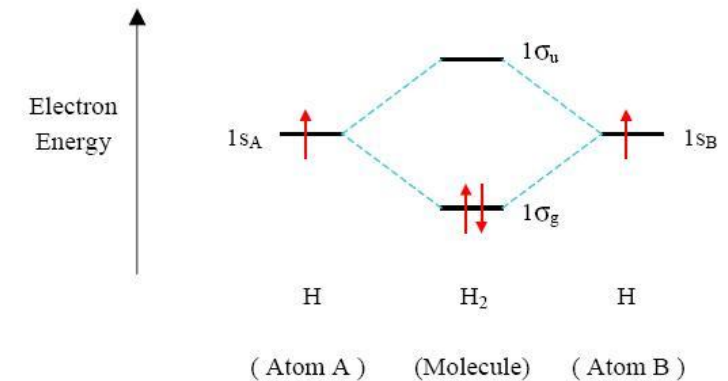
Quantum mechanics, however, provides energy states of **an atomic level**.



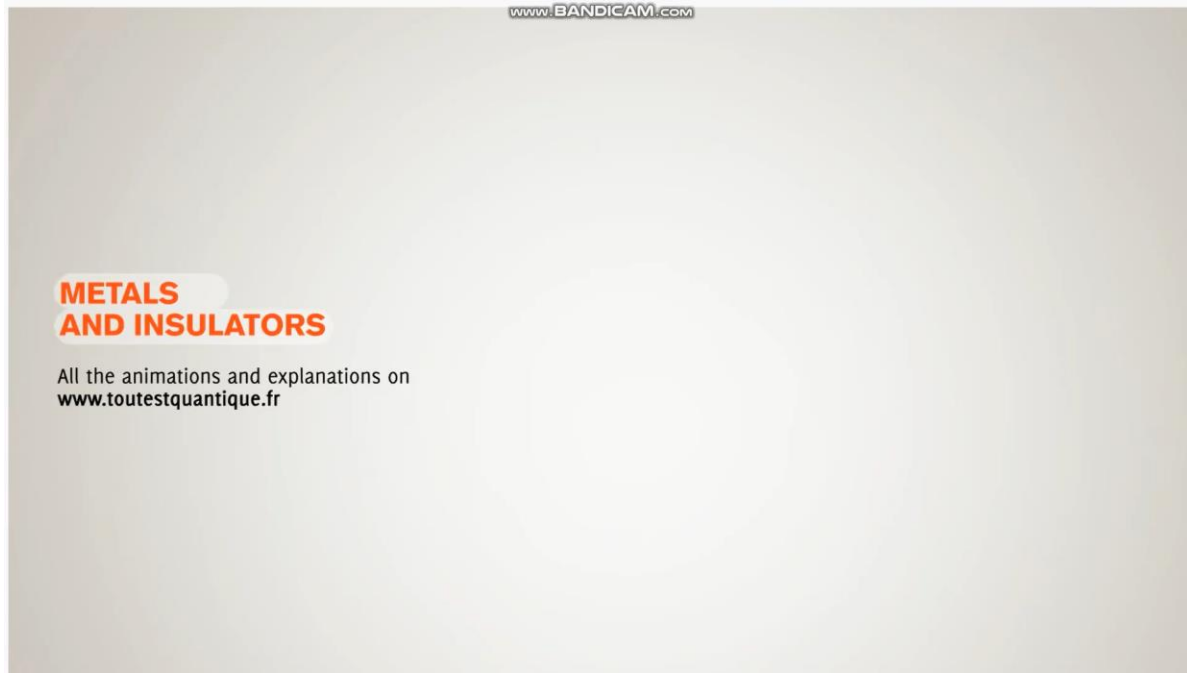
an atomic level energy level diagram

How about a molecule's energy state?

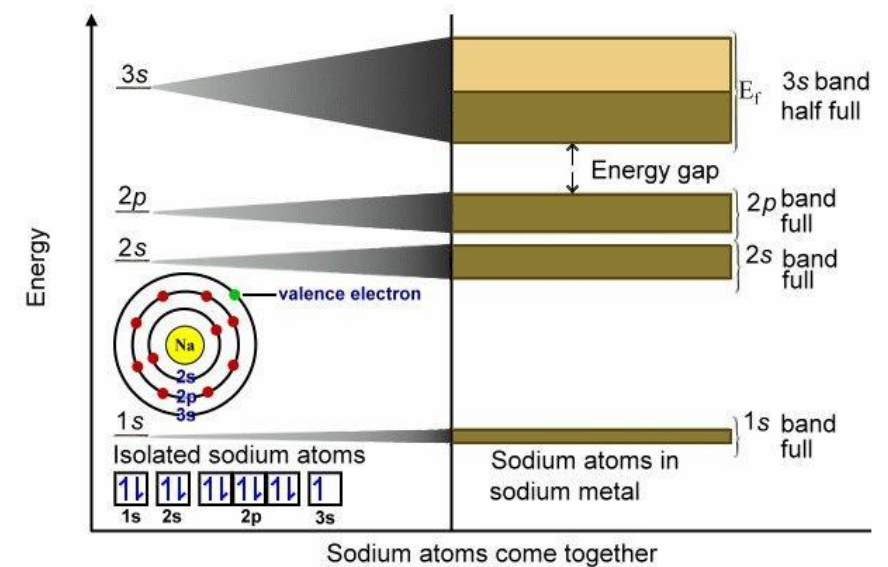
A covalent bond shares an electron, a wave function changes in a molecule. Probability of electrons in a molecule is explained by **molecular orbital theory**.



Then, how about a solid such as Si? A solid has tremendous amount of atoms in it.

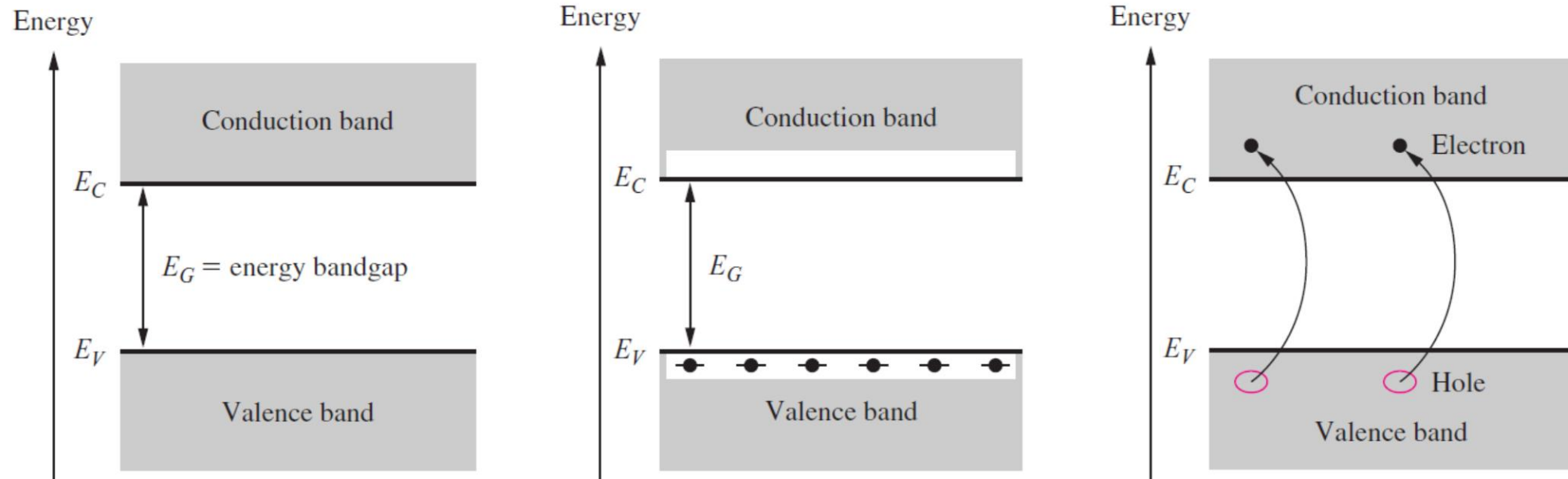


<http://toutestquantique.fr/en/research>



Energy band theory

In a solid, Energy level → Energy band due to large amount of electrons.



A conceptual picture of the band structure in the semiconductor. The regions labeled **conduction band** and **valence band** represent allowed energy states for electrons.

Energy E_V : The top edge of the **valence band** and represents the highest permissible energy for a valence electron.

Energy E_C : The bottom edge of the **conduction band** and represents the lowest available energy level in the conduction band.