Semiconductor Engineering

:Semiconductor Physics and Devices

Chapter 1. Semiconductor Electronics

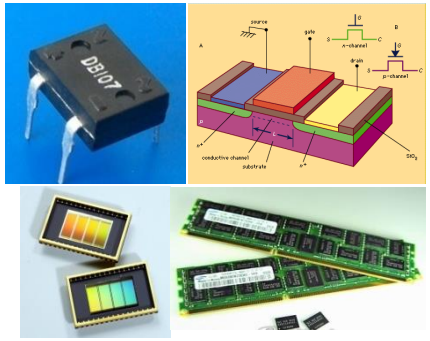
Why should we study semiconductor devices?

What is semiconductor engineering ?

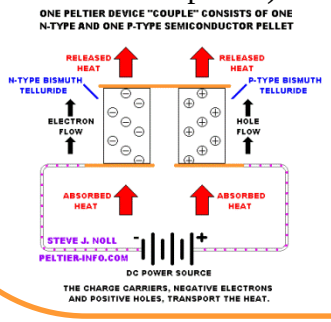
Study physics of semiconductors, devices and manufacturing methods.

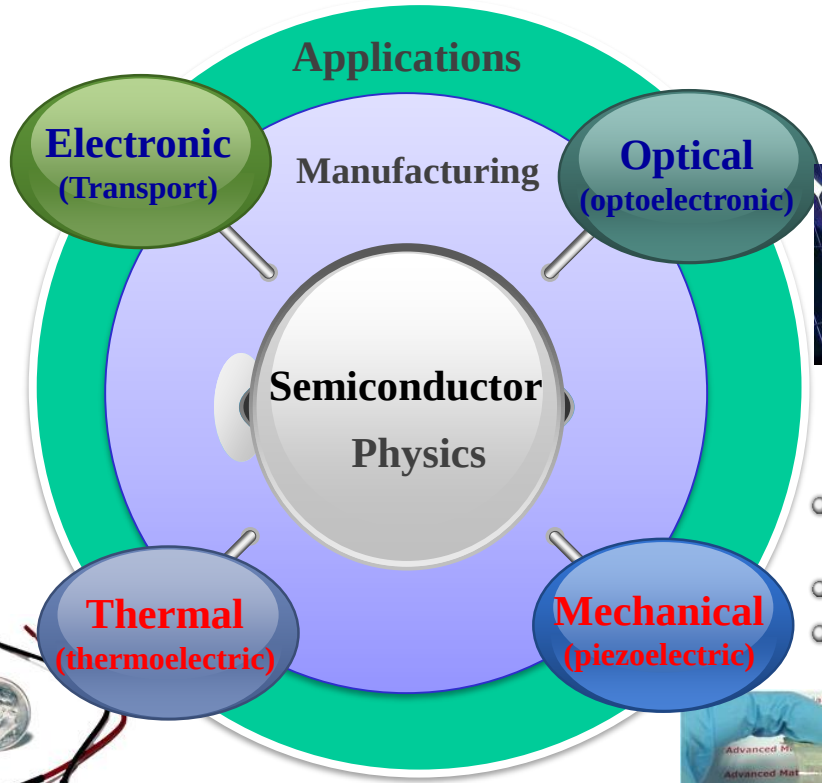
Semiconductor Engineering

- Diode
  (p-n, Zener, Varactor diodes)
- Transistors
  (bipolar, field effect: MOS, MIS)



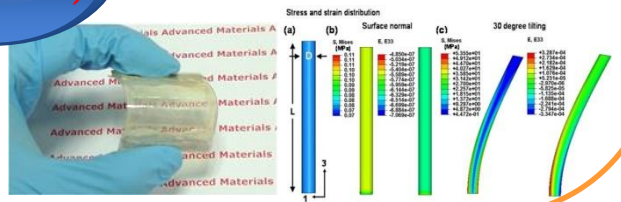
- Peltier thermal cooler
- Power generator
  (heat to electric power)





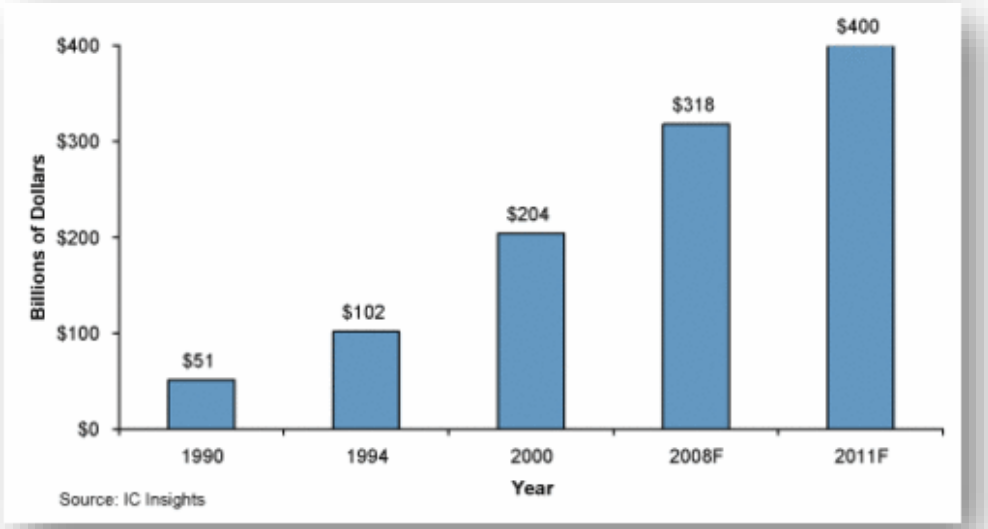
- Light-emitting diode
- Laser diode
- Photodiode
- Solar cell

- Power generator
  (Mechanical to electric power)
- RF sensor
- Crash sensor

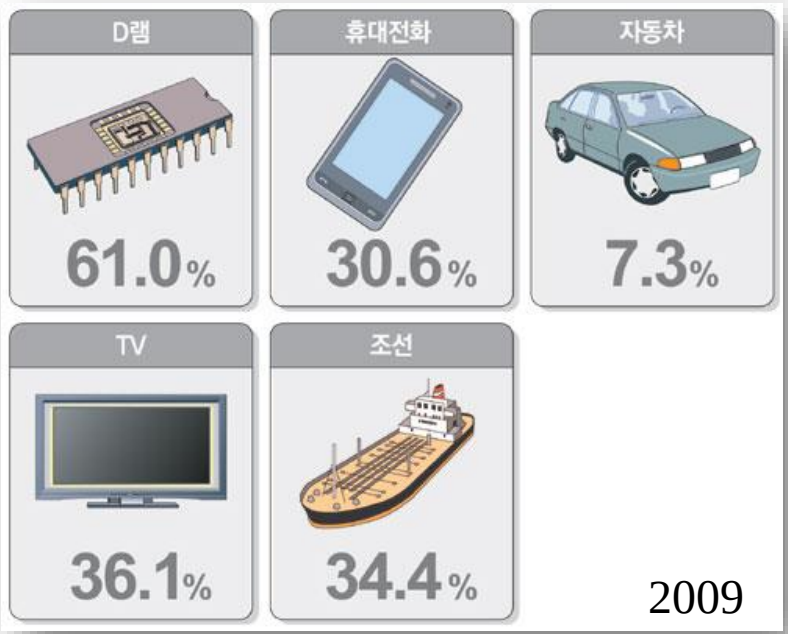


Why should we study semiconductor ?

Worldwide semiconductor market
(Silicon based semiconductors)



Korean important export items



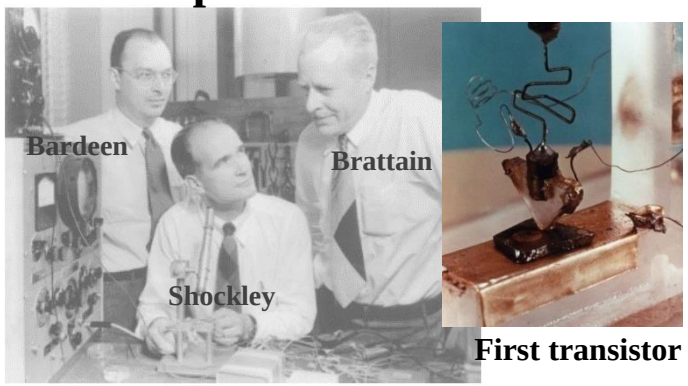
- Semiconductor devices are the foundation of the electronic industry, which is the largest in the world with global sales over one trillion dollars since 1998.
- For a long time, semiconductor industry has been and will be a main source of income in Korea.

Why should we study semiconductor?

Milestones of Silicon semiconductor industry

- 1947 : Invention of the Ge transistor at Bell Lab. (Bardeen, Brattain, Shockley)
- 1952 : Production of ultra-pure Si and Ge by zone refining technique at Bell Lab.
- 1955 : Invention of diffusion-based transistor at Bell Lab.
- 1958 : First demonstration of integrated circuit using mesa tech. at Texas Instruments.
- 1959 : Development of IC using planar process at Fairchild.
- 1959 : Invention of the MOSFET at Bell Lab.
- 1960's : Complete the planar process and IC fabrication process.
- 1970's ~ 80's : Market and technology development

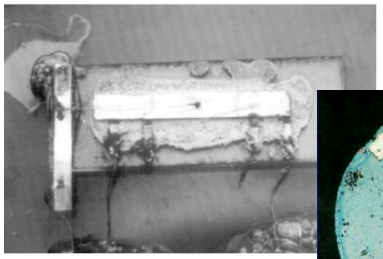
First bipolar transistor



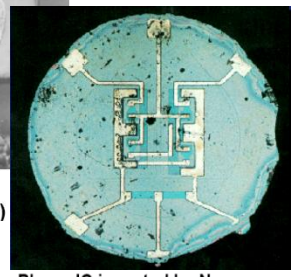
First transistor

Nobel Prize (Physics) @1956

First integrated circuit



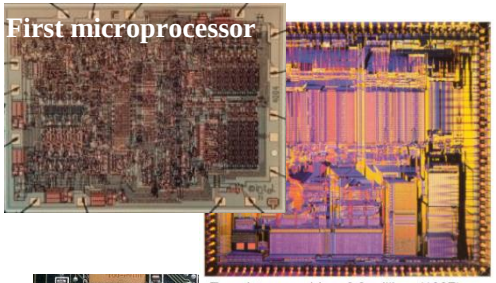
Kilby's first IC
(Texas Instruments, 1958)



Planar IC invented by Noyce
(Fairchild Semiconductor, 1959)

Nobel Prize (Physics) @2000

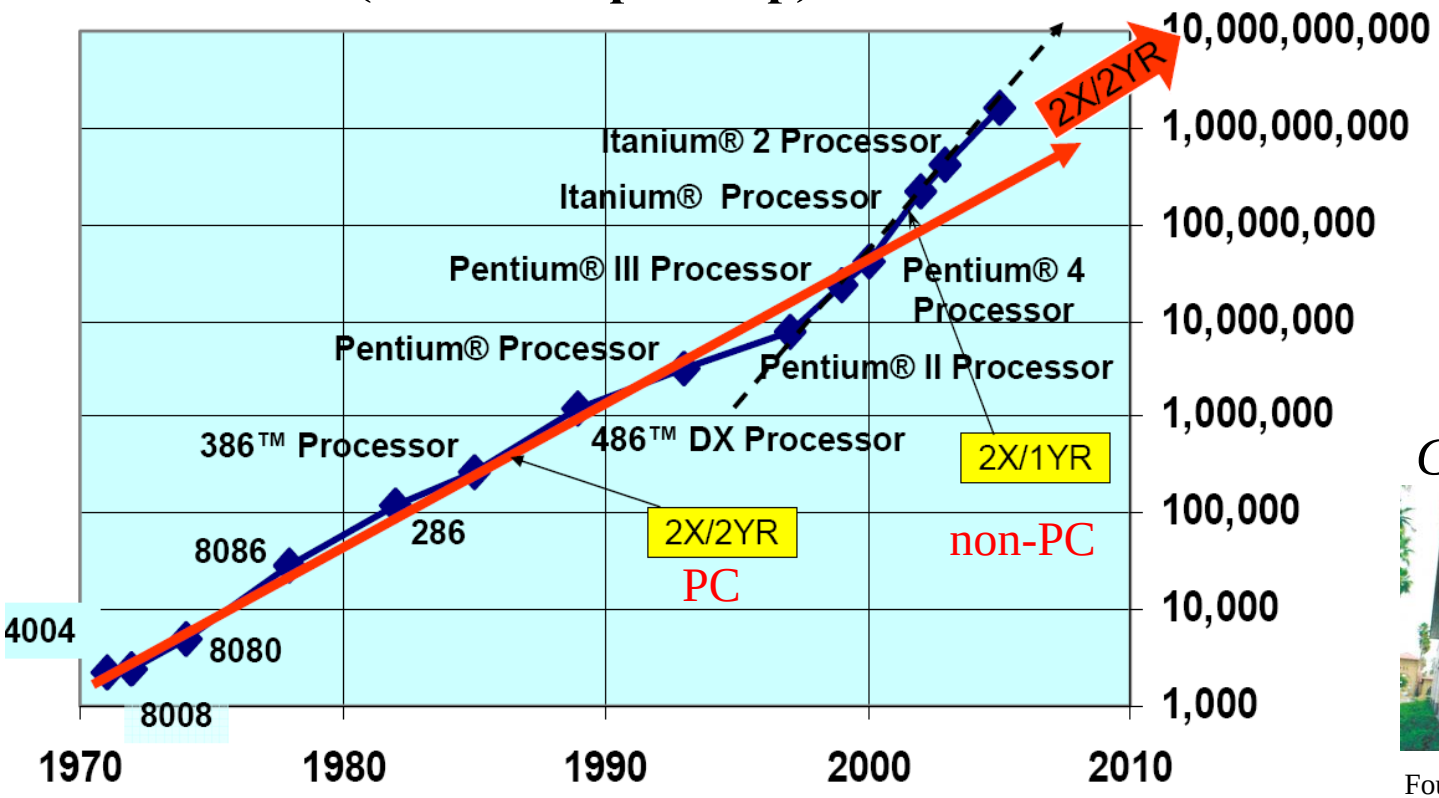
Microprocessor



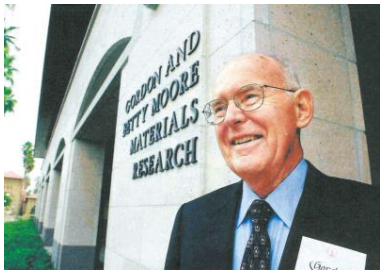
Transistor per chip ~ 0.3 million. (1987)
Equivalent to an Intel 386 microprocessor.

Why should we study semiconductor?

Moore's Law (Functions per chip)



Gordon Moore



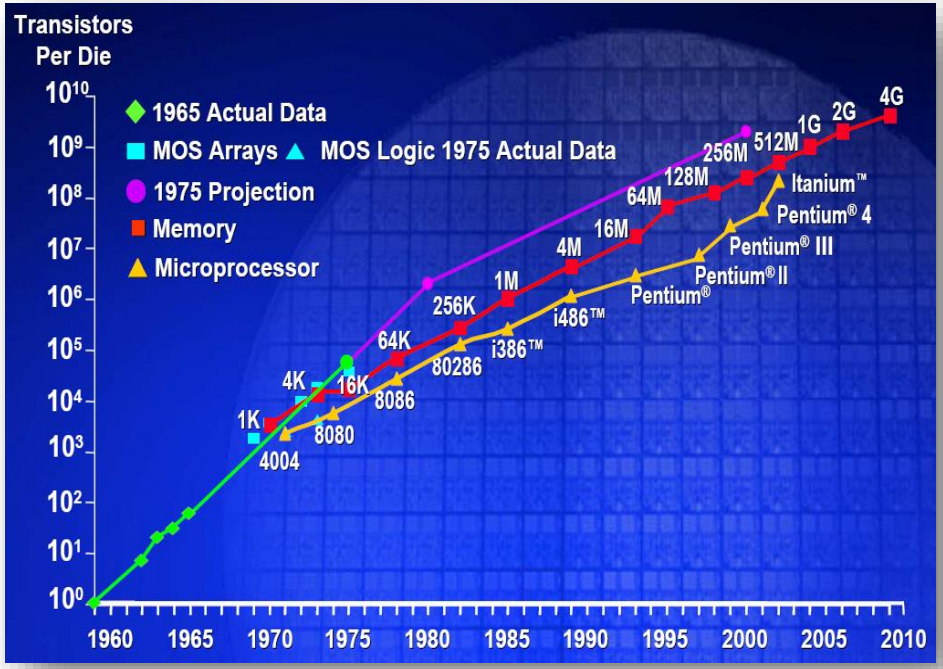
Founder and former CEO of Intel

The number of transistors that can be placed inexpensively on an integrated circuit has doubled approximately every two years.

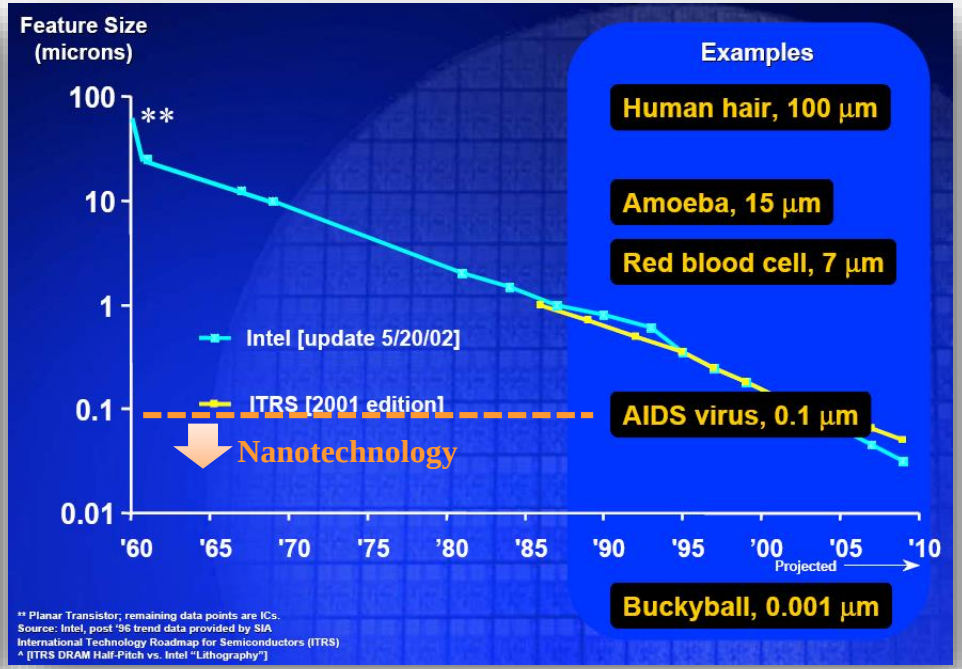
➔ **Development of semiconductor technology is getting more and more important !!**

History of Silicon semiconductor industry

IC Development at Intel



Minimum Feature size reduction



Source : Intel

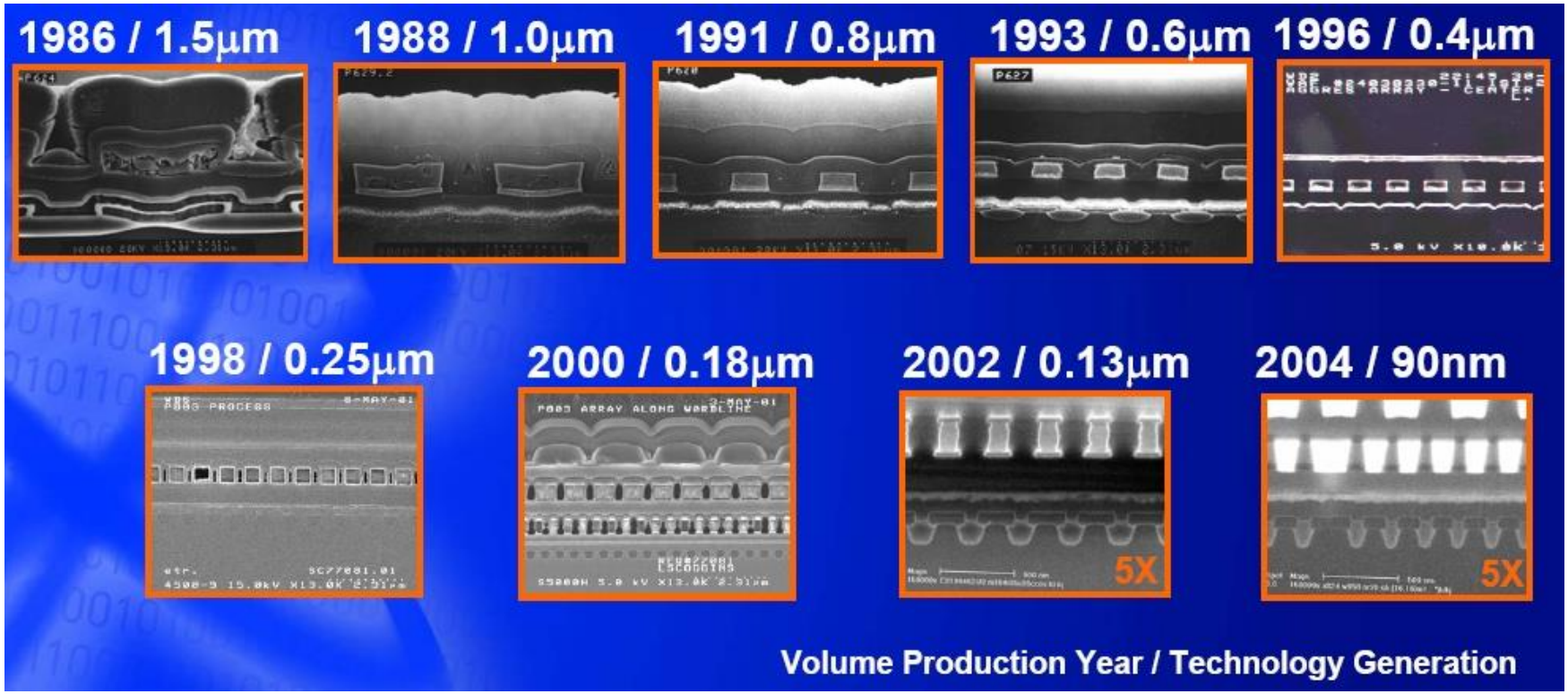
Minimum feature size is the width of the smallest line or gap that appears in the IC design. (depends on equipments and technology)

➔ Indication of the technology development

➔ **Development of semiconductor technology is getting more and more important !!**

Why should we study the Semiconductor?

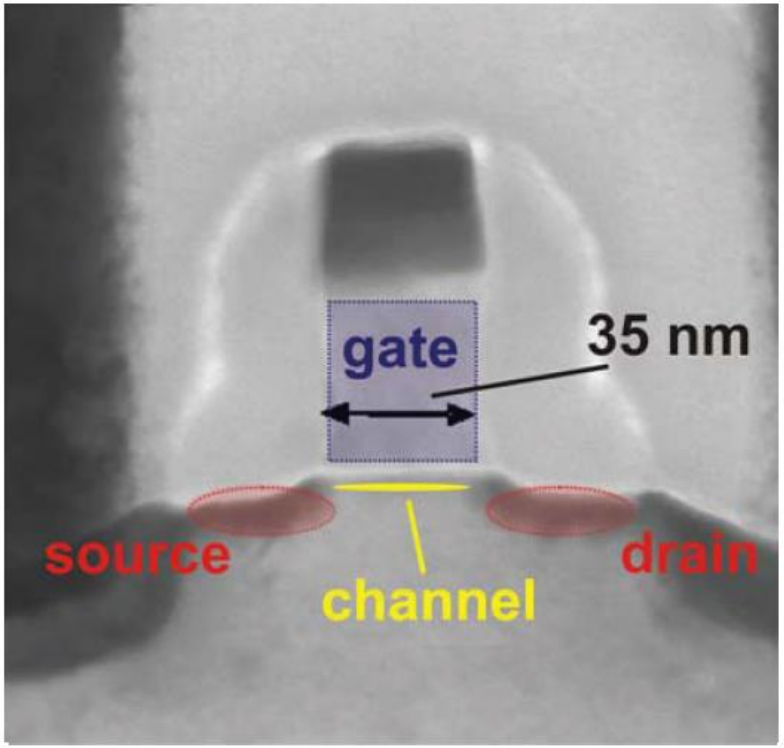
Minimum feature size reduction with time



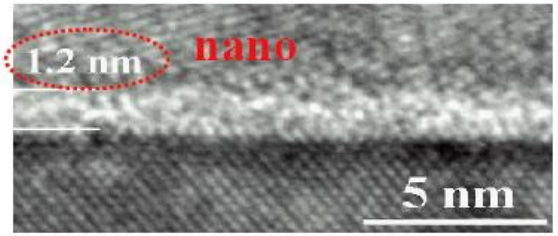
Today	▪ Flash / DRAM
Future	▪ Alternate memory : MRAM, FeRAM ▪ Nanoelectronics ▪ Optoelectronics ▪ Bioelectronics / Organic electronics

Understanding and development of new technology based on semiconductor engineering is required for electronic engineers !!

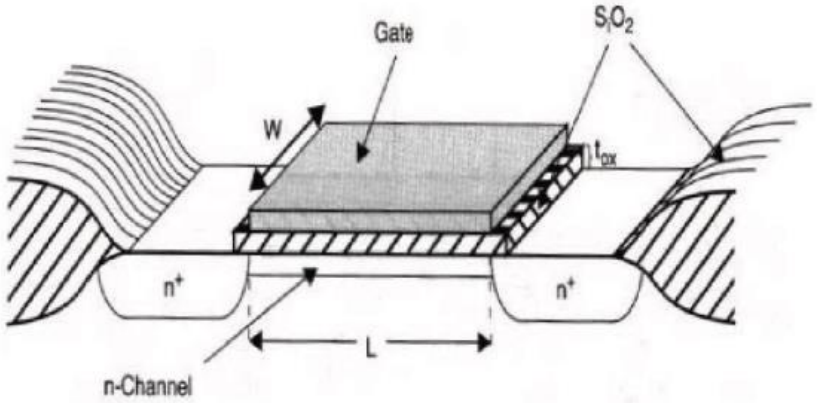
The incredible shrinking of the transistor !!

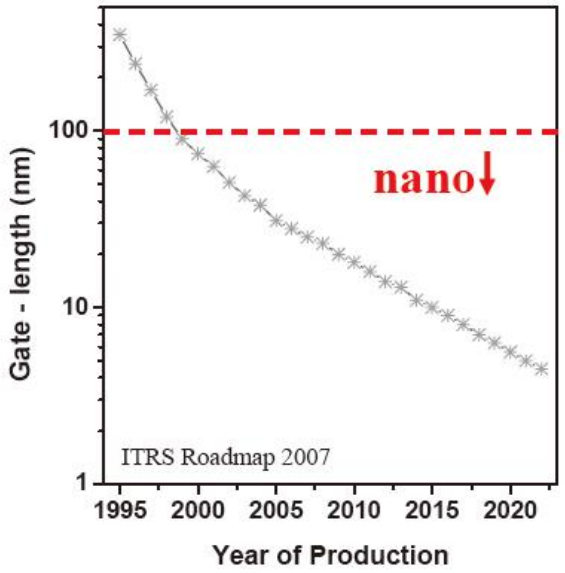


TEM image of a contemporary FET



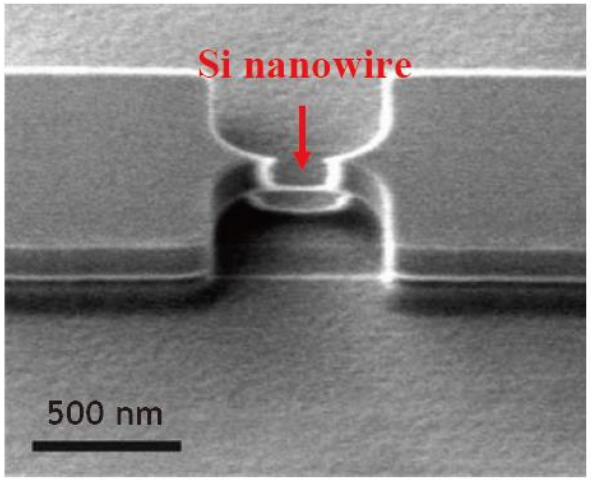
Electronmicroscope image of a SiO_2 **gate insulator** LETI, CEA, France

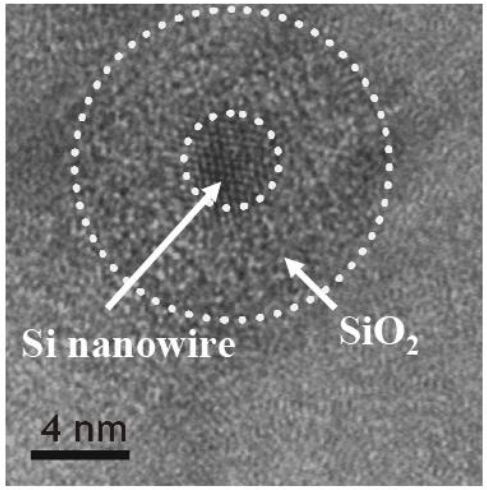


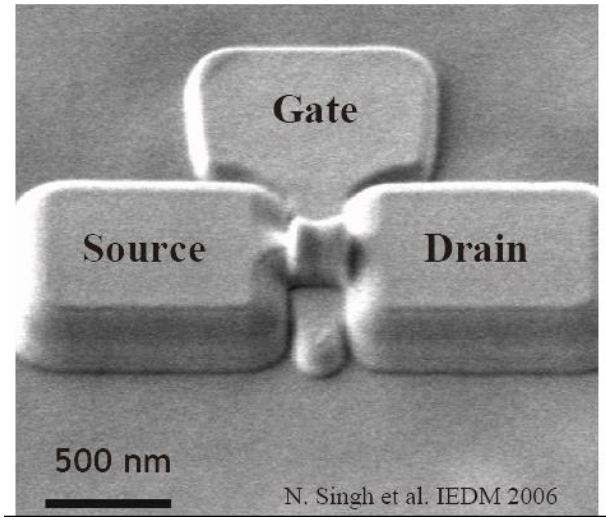


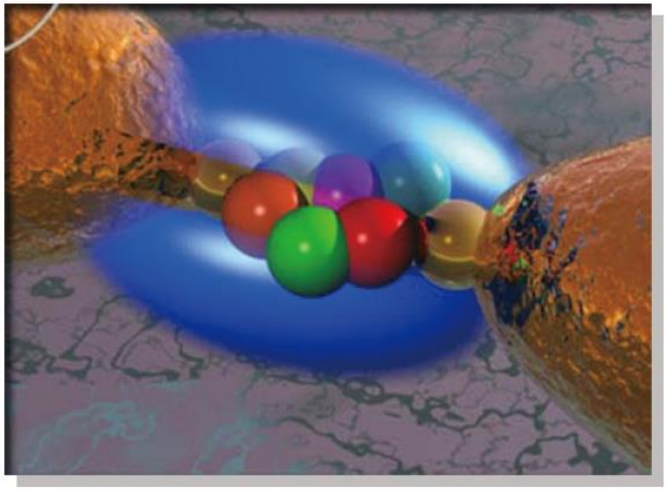
The incredible shrinking of the transistor !!

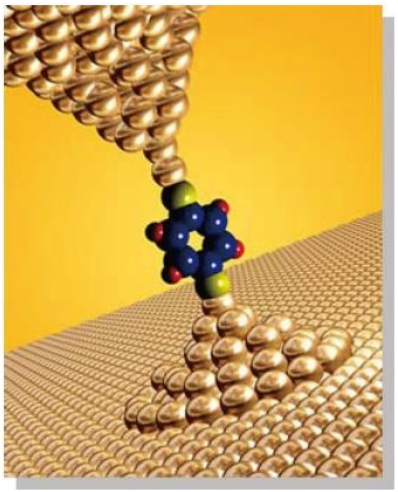
Nanoelectronics and molecular electronics











Objectives

Chapter 1. Semiconductor Electronics

Overview of the physical electronics of semiconductor

- Energy band theory
- Doping principle
- Free carrier statistics
- Drift and diffusion

Electronic properties of materials

How do know the electrical properties materials?

Resistance: *R*

$$R = V/I \qquad \textit{From Ohm's law}$$

the current *I* flowing through a bar of homogeneous material with uniform cross section when a voltage *V* is applied across it, we can find its resistance *R*

Resistivity: ρ

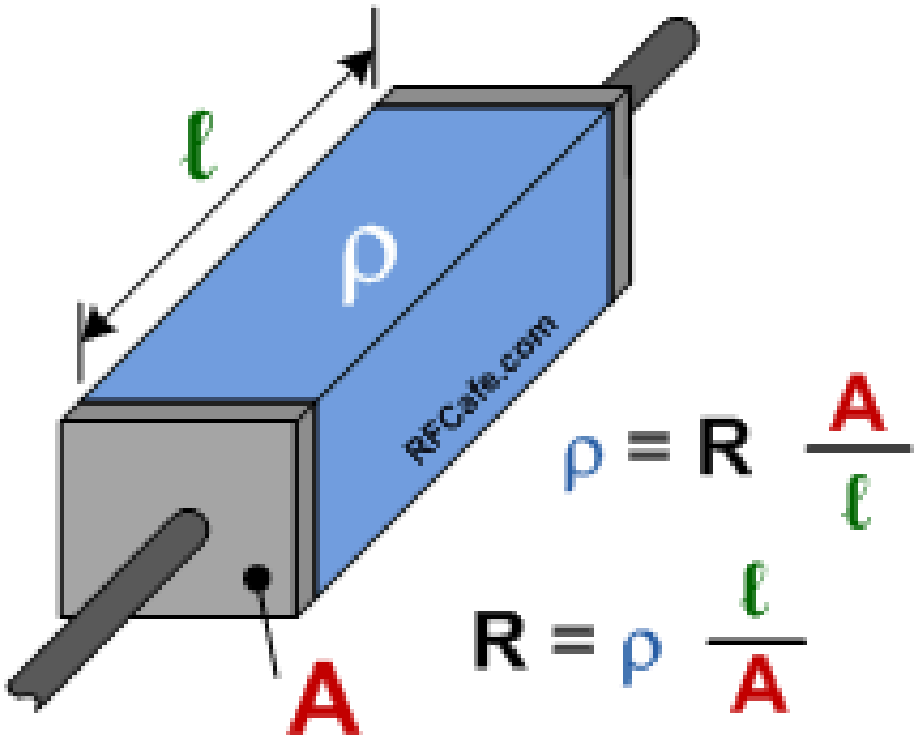
$$\rho = R\frac{A}{L}$$

is related to the resistance of the bar by a geometric ratio where L and A are the length and cross-sectional area of the sample

Electronic properties of materials

How do know the electrical properties materials?

Resistance: *R* Resistivity: ρ



Resistivity

The resistivity of common materials used in solid-state devices cover a wide range

An example is the range of resistivities encountered at room temperature for the materials used to fabricate typical silicon integrated circuits

Resistivities of 10^{-6} Ω-cm at room temperature

: very low-resistivity materials, connect elements of the integrated circuit; aluminum and copper

Resistivities of 10^{16} Ω-cm at room temperature

: the resistivity scale are insulating materials such as silicon dioxide, which serve to isolate portions of the integrated circuit

Resistivities of 10^{18} Ω-cm at room temperature

: the resistivity of the plastics often used to encapsulate integrated circuits

Classification by resistivity

Materials are generally classified according to their resistivities (ρ)

Conductor

: Resistivities less than 10^{-2} Ω-cm

Insulator

: Resistivities greater than 10^{5} Ω-cm

Semiconductor

: Intermediate resistivities region

→ resistivities can be varied by design and precisely controlled

→ can be made to conductor by one of two types of current carriers (electron / hole)

Physics of Semiconductor Materials

An understanding of the physics of electrons in solid

: achieved by first considering electrons in an isolated atom

→ resistivities can be varied by design and precisely controlled

Considering allowed energies of electron influenced by an isolated atom

In solid materials (many atoms system)

→ we have to look at the effect of bringing other atoms near the first atom

→ Study the effect of the atomic core in crystal on the behavior of the associated electron

→ Investigate the effect on the electron of applied electric field to the solid materials

➡ *Energy band model / Crystal-bonding model*

Band model of solids

Energy band in solids

There are discrete energy levels in the case of an isolated atom

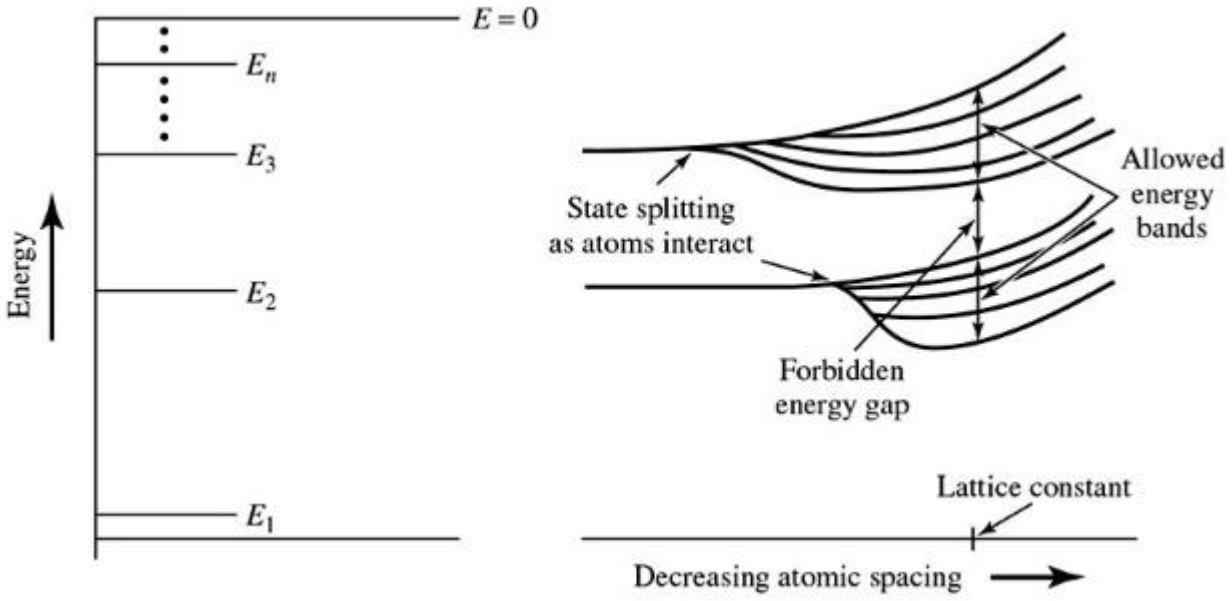


Figure 1.1 (a) Allowed energy levels of an electron acted on by the Coulomb potential of an atomic nucleus (b) splitting of the energy state into allowed bands separated by a forbidden energy gap as the atomic spacing decreases; the electrical properties of a crystalline material correspond to specific allowed and forbidden energies associated with an atomic separation related to the lattice constant of the crystal.

Band model of solids

Case 1: Isolated atom

Allowed series of energy level that electron can occupy

$$E_n = -\frac{me^4}{8\varepsilon_o{}^2 h^2}\left(\frac{Z^2}{n^2}\right)$$

See on page 2~3 of the text book

Case 2: More than one electron are associated

The electrons filled the allowed levels starting with the lowest energies.

→ By the Pauli exclusion principle, at most two electrons (of opposite spins) can occupy any energy level.

If two atoms approach on another (atoms are close together)

→ the atomic core of the first atom exerts a force on the second electron, changing the potential the determines the energy levels of the electron

→ All allowed energy levels for the electron are consequently modified

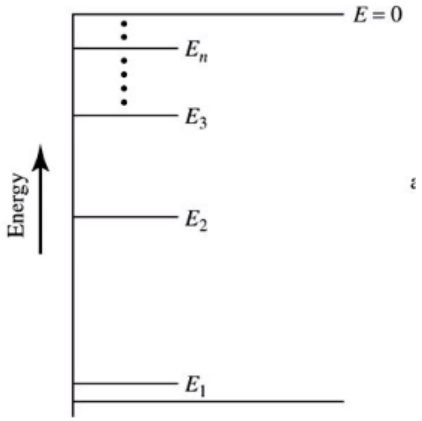
Band model of solids

Two atom system with two electron

Isolated (separated) two atoms

An energy level, E_n

Contain at most two electrons of opposite spin, total system contain at most four electrons



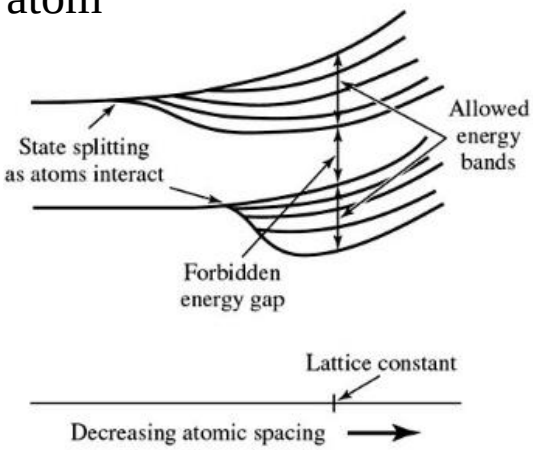
When the isolated two atoms are brought together to form one system

Bringing two atoms close together

→ slightly perturbs each energy level of the isolated atom

→ splits each of the energy levels of the isolated atoms into two slightly separated energy levels

→ As two atoms are brought closer together, stronger interaction are expected and the splitting increases



Band model of solids

Many atoms form a crystalline structure

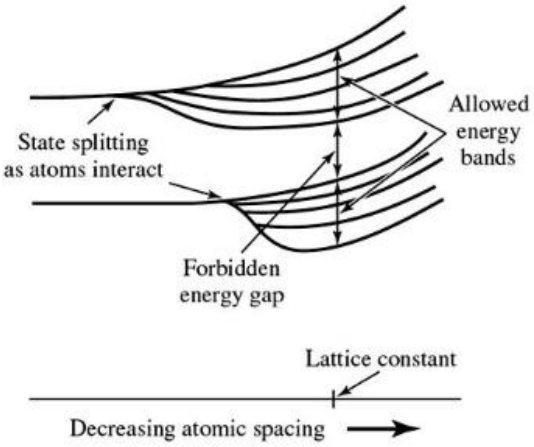
the forces encountered by each electron are altered further, and additional changes in the energy levels occur

→ Pauli exclusion principle demands that each allowed electron energy level have a slightly different energy so that many distinct, closely spaced energy levels characterize the crystal.

When *N* atoms are included in the system

the original *energy level* E_n splits into *N* different allowed levels, forming an *energy band*, which may contain at most *2N* electrons (because of spin degeneracy)

→ the discrete energies that characterize isolated atoms split into multiple levels as the atomic spacing decreases. When the atomic spacing equals the crystal-lattice spacing



Band model of solids

Broadening of allowed energy levels into allowed energy bands separated by *forbidden-energy gaps* as more atoms influence **each electron in a solid**

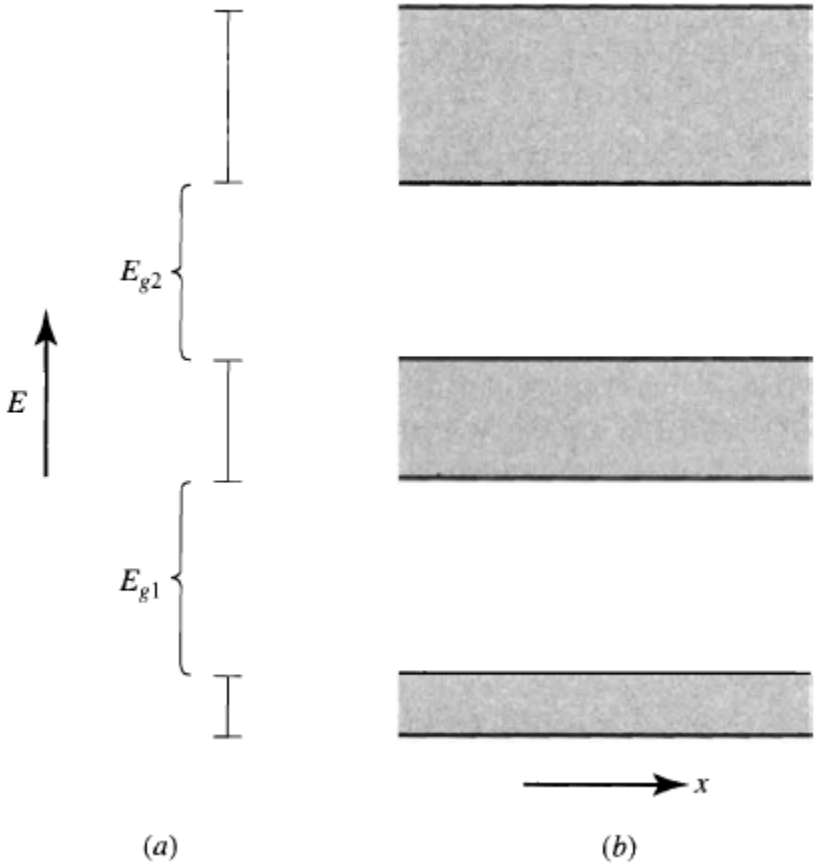


FIGURE 1.2 Broadening of allowed energy levels into allowed energy bands separated by forbidden-energy gaps as more atoms influence each electron in a solid: (*a*) one-dimensional representation; (*b*) two-dimensional diagram in which energy is plotted versus distance.

Band model of solids

Bohr radius r_n associated with the nth energy level:

$$r_n = \frac{n^2 \epsilon_0 h^2}{Z \pi m_0 q^2} = \frac{n^2}{Z} \times 0.0529 \text{ nm}$$

For higher energy levels (larger *n)* the electron is less tightly bound and can wander farther from the atomic core.

If the electron is less tightly confined, it comes closer to the adjacent atoms and is more strongly influenced by them.

This greater interaction causes a larger change in the energy levels so that the wider energy bands correspond to the higher energy electrons of the isolated atoms.

Band model of solids

The formation of energy bands from discrete levels occurs whenever the atoms of any element are brought together to form a solid.

Consider first an alkali metal composed of *N* atoms, each with one valence electron in the outer shell. When the atoms are brought close together, an energy band forms from this energy level. In the simplest case this band has space for *2N* electrons. The *N* available electrons then fill the lower half of the energy band and there are empty states just above the filled states.

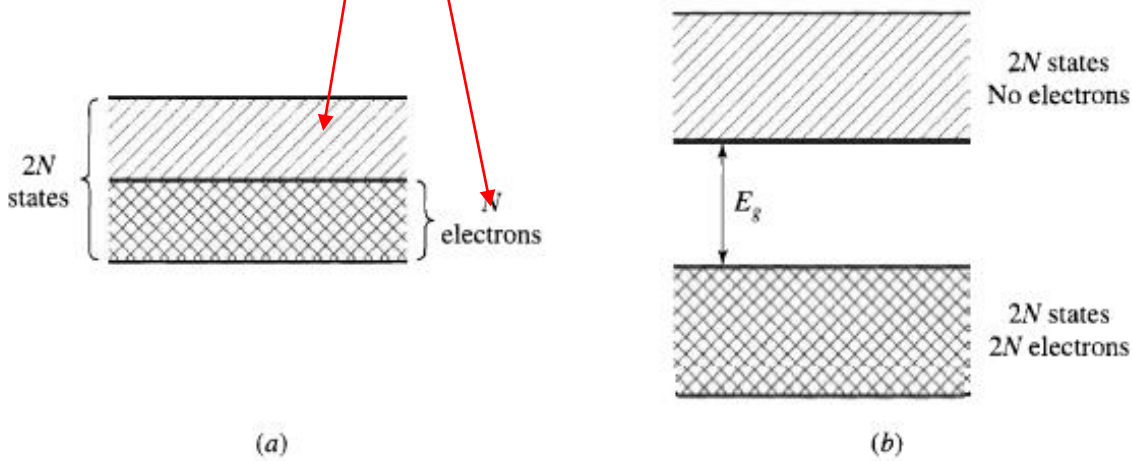


FIGURE 1.3 Energy-band diagrams: (*a*) *N* electrons filling half of the 2*N* allowed states, as can occur in a metal. (*b*) A completely empty band separated by an energy gap E_g from a band whose 2*N* states are completely filled by 2*N* electrons, representative of an insulator.

Band model of solids

Band structure of metal

The electrons near the top of the filled portion of the band can easily gain small amounts of energy from an applied electric field and move into these empty states.

→ partially fill electrons behave almost as free electrons and can be transported through the crystal by an externally applied electric field

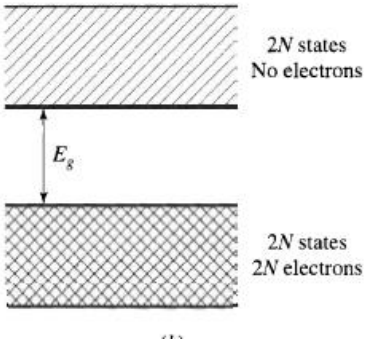
(a)

Band model of solids

Band structure of insulator

the valence (outermost shell) electrons completely fill an allowed energy band and there is an energy gap to the next higher band

the closest allowed band above the filled band is completely empty at low temperatures



The lowest-energy empty states are separated from the highest filled states by the energy gap E_g.
In insulating material, E_g is generally greater than 5 e V (~8-9 e V for SiO_2), much larger than typical thermal or field-imparted energies (tenths of an eV or less).

→ no electrons close to empty allowed states and, therefore, no electrons can gain small energies from an externally applied field. Consequently, no electrons can carry an electric current, and the material is an insulator.

Band model of solids

Electron motion in metal and insulator

Metal

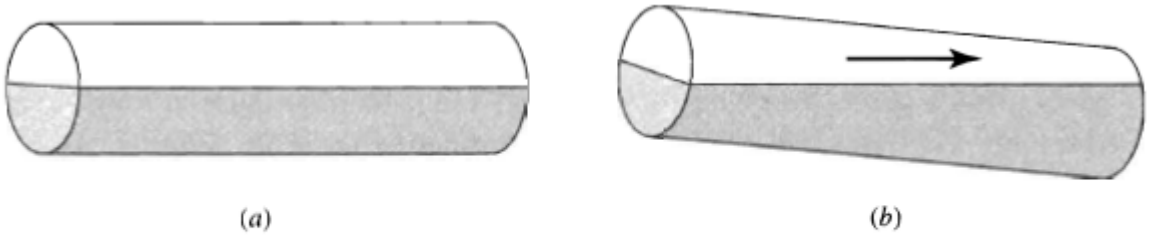


FIGURE 1.4 Electron motion in an allowed band is analogous to fluid motion in a glass tube with sealed ends; the fluid can move in a half-filled tube just as electrons can move in a metal.

→ When a force (gravity in this case) is applied by tipping the tube, the fluid can easily move along the tube.

Insulator

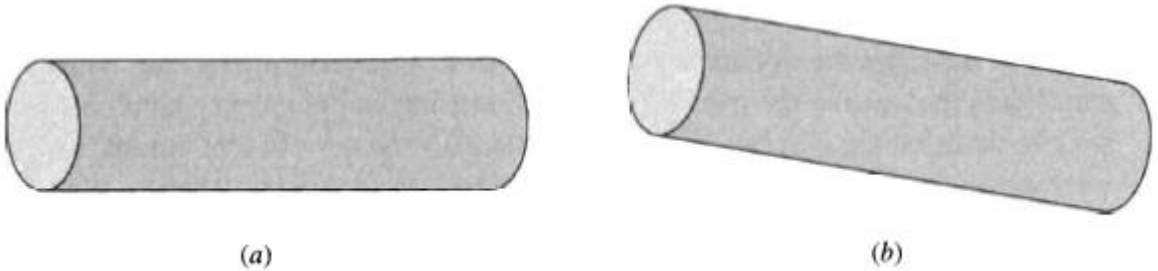


FIGURE 1.5 No fluid motion can occur in a completely filled tube with sealed ends.

→ When the filled tube is tipped, the fluid cannot flow because there is no empty volume into which it can move; that is. there are no empty allowed states.

Band model of solids

Band structure of semiconductor

Both electrical insulators and semiconductors have similar band structures.

The electrical difference between insulators and semiconductors arises from the size of the forbidden-energy gap and the ability to populate a nearly empty band by adding conductivity enhancing impurities to a semiconductor.

e.g. the energy gap separating the highest band that is filled at absolute zero temperature from the lowest empty band is typically of the order of 1 eV

Silicon (Si): 1.1 eV

Germanium (Ge): 0.7 eV

Gallium arsenide (GaAs): 1.4 eV

Band model of solids

Band structure of semiconductor

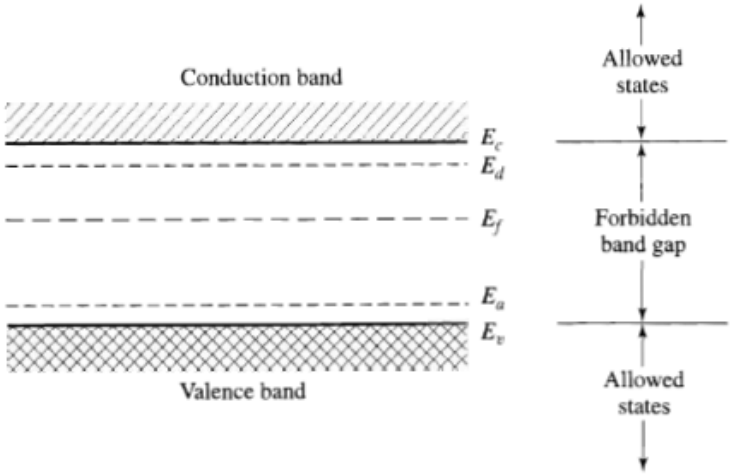


FIGURE 1.6 Energy-band diagram for a semiconductor showing the lower edge of the conduction band E_c, a donor level E_d within the forbidden gap, the Fermi level E_f, an acceptor level E_a, and the top edge of the valence band E_v.

At any temperature above absolute zero, the valence band is not entirely filled because a small number of electrons possess enough thermal energy to be excited across the forbidden gap into the next allowed band.

→ The smaller the energy gap and the higher the temperature, the greater the number of electrons that can jump between bands. The electrons in the upper band can easily gain small amounts of energy and can respond to an applied electric field to produce a current.

→ This band is called the *conduction band* because the electrons that populate it are conductors of electricity.

Band model of solids

Band structure of semiconductor

Current flow in the conduction band

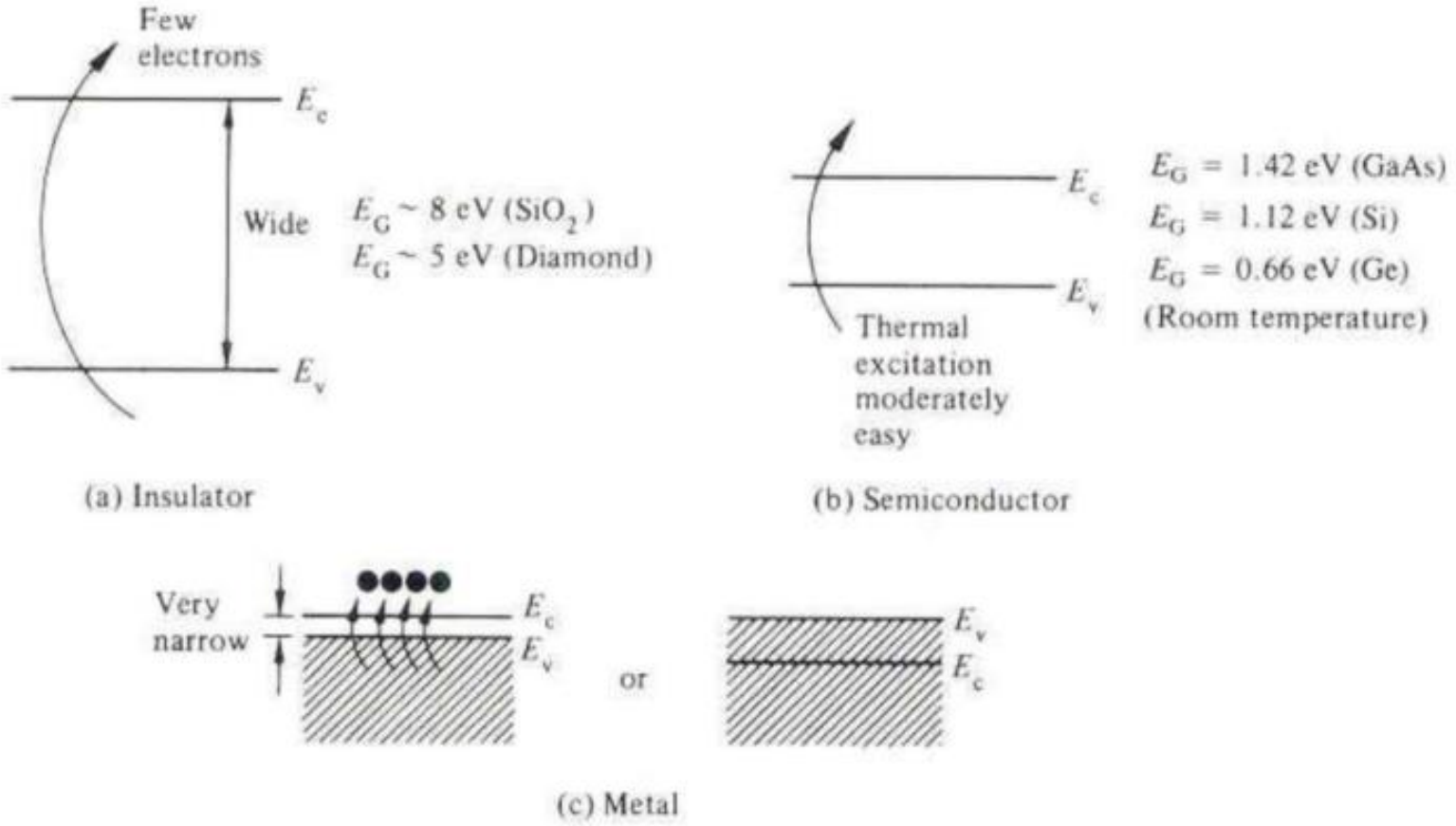
$$J_{cb} = \frac{I}{A} = \sum_{cb} (-q) v_i$$

summing the charge *(-q)* times the net velocity *(v_i)* of each electron populating the band

Current density at conduction band

Band model of solids

Band structure of insulator, semiconductor, metal



Holes

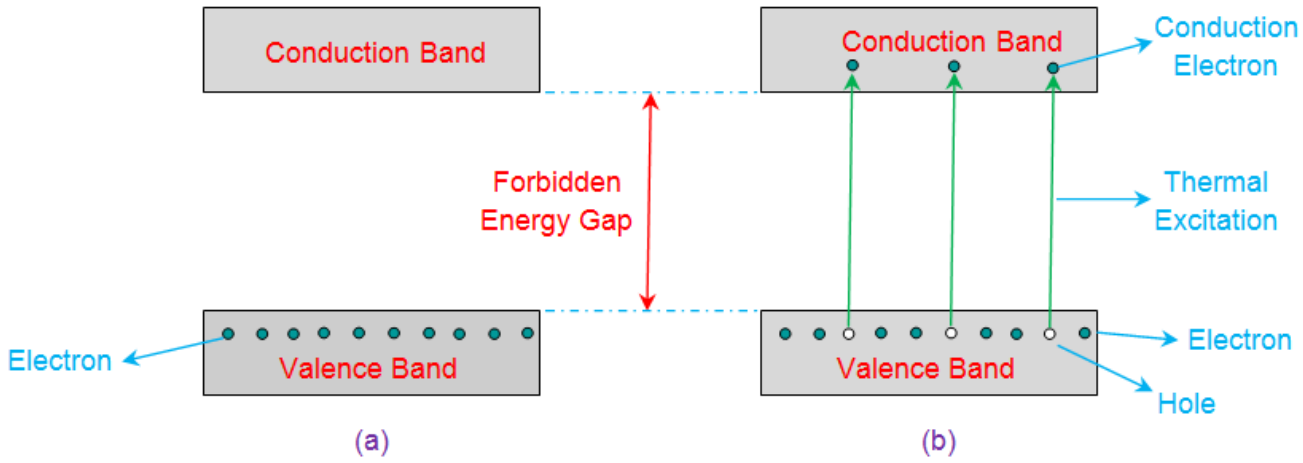


Figure 2 Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K

When electrons are excited into the conduction band, empty states are left in the valence band.
If an electric field is then applied, nearby electrons can respond to the field by moving into these empty states to produce a current

Holes

Current flow in the valance band

$$J_{vb} = \sum_{vb} (-q) v_i$$

summing the motion of all electrons in the valence band of a unit volume of the material.

Mathematically, we can describe the current in the valence band as the current that would flow if the band were completely filled minus that associated with the missing electrons.

$$J_{vb} = \sum_{vb} (-q) v_i = \sum_{Filled\ band} (-q) v_i - \sum_{Empty\ states} (-q) v_i$$

since no current can flow in a completely filled band

the current in the valence band $J_{vb} = 0 - \sum_{Empty\ states} (-q) v_i = \sum_{Empty\ states} q v_i$

the motion of charge in the valence band in terms of the vacant states by treating the states as if they were particles with positive charge; “hole”

Holes

Hole

Current flow in the valance band

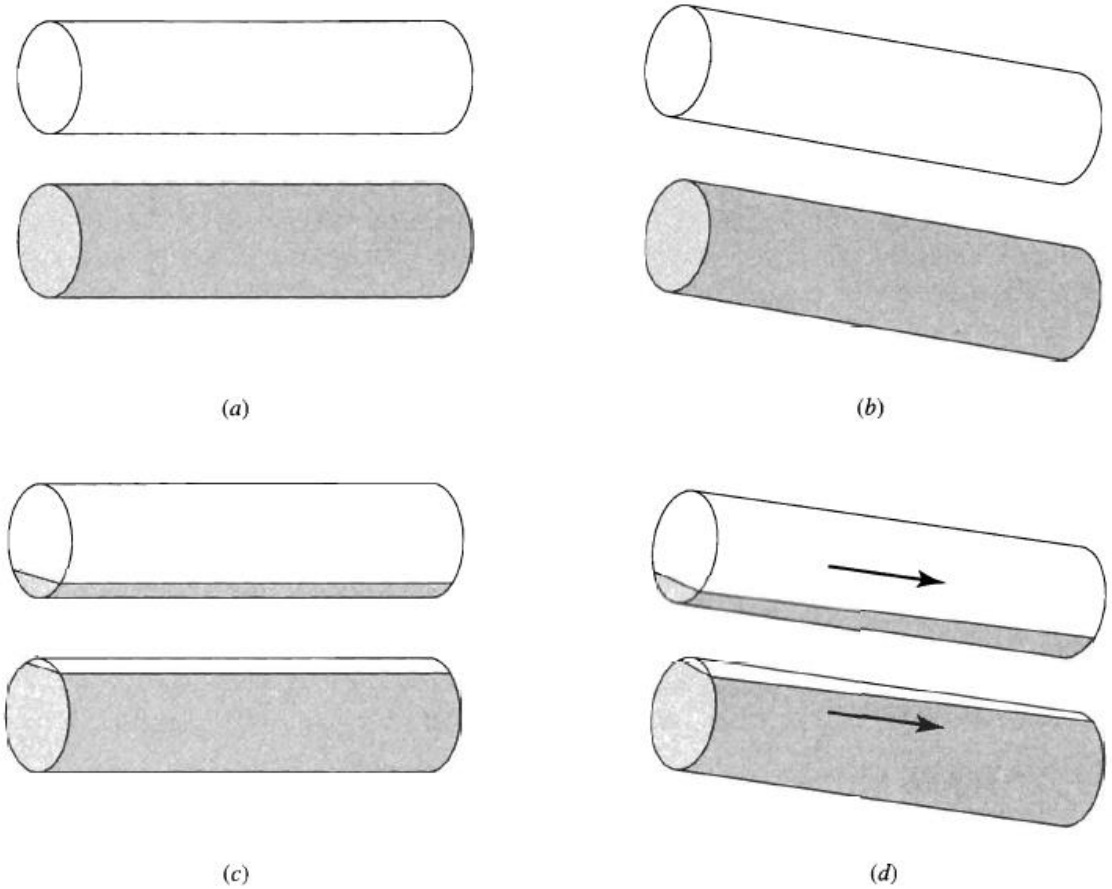


FIGURE 1.7 Fluid analogy for a semiconductor. (*a*) and (*b*) No flow can occur in either the completely filled or completely empty tube. (*c*) and (*d*) Fluid can move in both tubes if some of it is transferred from the filled tube to the empty one, leaving unfilled volume in the lower tube.

Bond Model

Bond model

Free holes and electrons in semiconductorscan also be phrased in terms of the behavior of completed and broken electronic bonds in a semiconductor crystal

→ Hard to account for important quantum mechanical constraints on the behavior of electrons in crystals, but useful qualitative concepts.

Consider diamond-type crystal structure

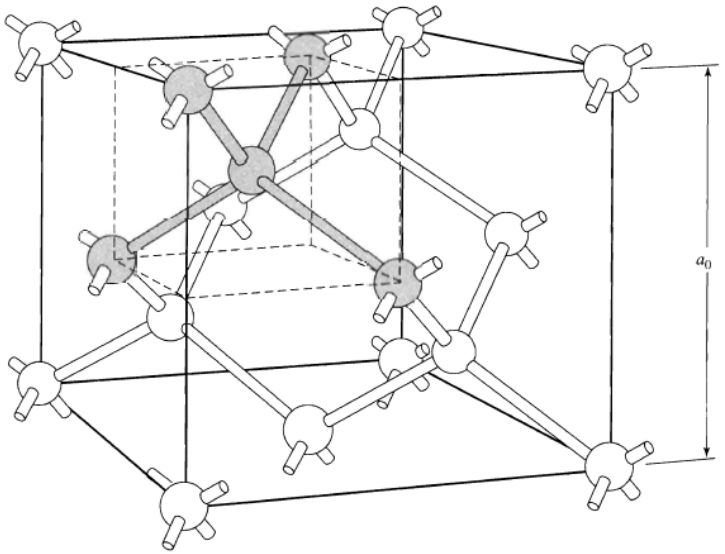


FIGURE 1.8 The diamond-crystal lattice characterized by four covalently bonded atoms. The lattice constant, denoted by a_0, is 0.356, 0.543 and 0.565 nm for diamond, silicon, and germanium, respectively. Nearest neighbors are spaced $(\sqrt{3}a_0/4)$ units apart. Of the 18 atoms shown in the figure, only 8 belong to the volume a_0^3. Because the 8 corner atoms are each shared by 8 cubes, they contribute a total of 1 atom; the 6 face atoms are each shared by 2 cubes and thus contribute 3 atoms, and there are 4 atoms inside the cube. The atomic density is therefore $8/a_0^3$, which corresponds to 17.7, 5.00, and 4.43×10^{22} cm^{-3}, respectively. (After W. Shockley: *Electrons and Holes in Semiconductors*, Van Nostrand, Princeton, N.J., 1950.)

Bond Model

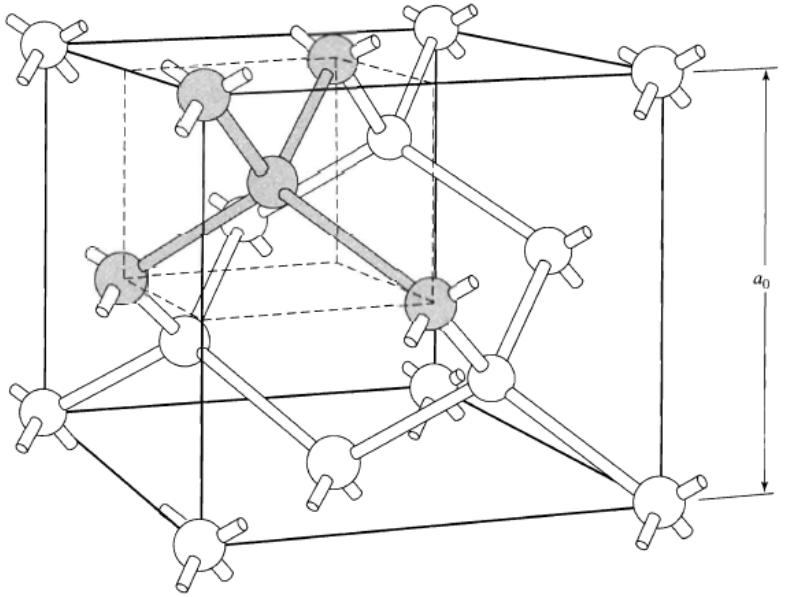
Consider diamond-type crystal structure

→ each atom has covalent bonds with its four nearest neighbors

two tightly bound electrons associated with each bond-one from each atom

At absolute zero temperature,
all electrons are held in these bonds, and therefore none are free to move about the crystal in response to an applied electric field.

At higher temperatures,
thermal energy breaks some of the bonds and creates nearly free electrons, which can then contribute to the current under the influence of an applied electric field



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Bond Model

At higher temperatures,
thermal energy breaks some of the bonds and creates nearly free electrons

→ freed electron moves away, an empty bond is left behind

→ An electron from an adjacent bond can then jump into the vacant bond, leaving a vacant bond behind

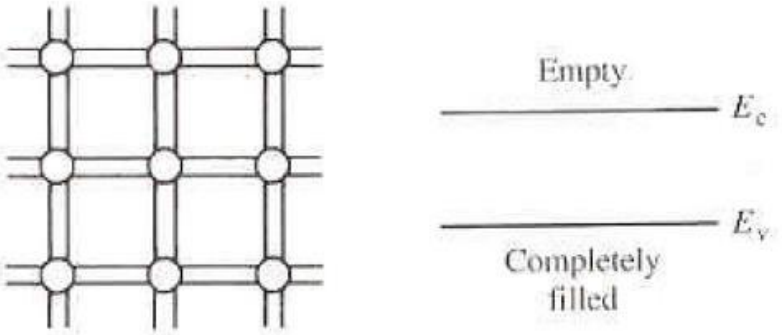
→ The vacant bond, therefore, moves in the opposite direction to the electrons.

If a net motion is imparted to the electrons by an applied field, the vacant bond can continue moving in the direction opposite to the electrons as if it had a positive charge.

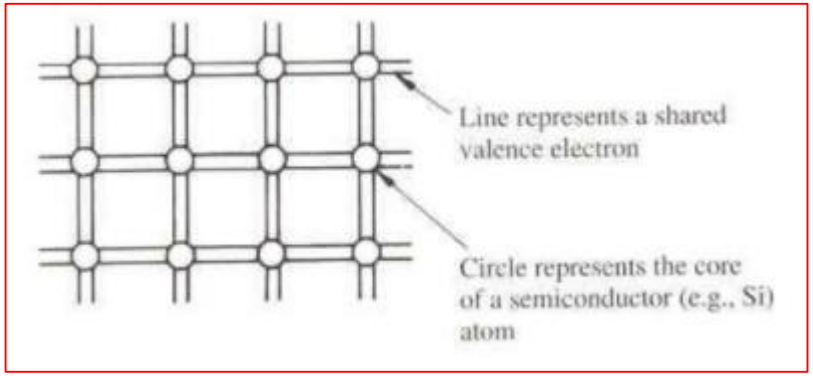
→ This vacant bond corresponds to the hole associated with the valence band in the energy-band picture.

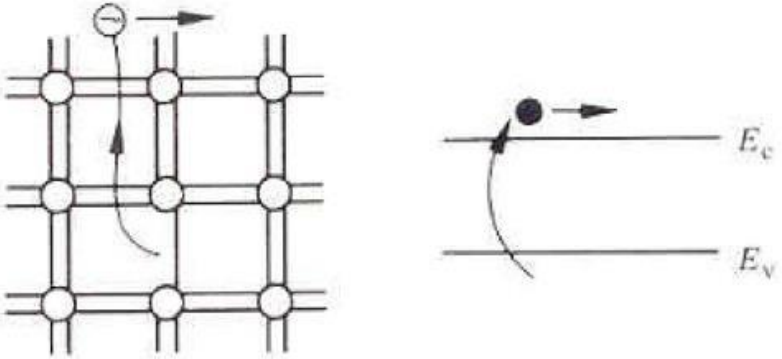
Bond Model

Band vs. Bond model for electronic band structure

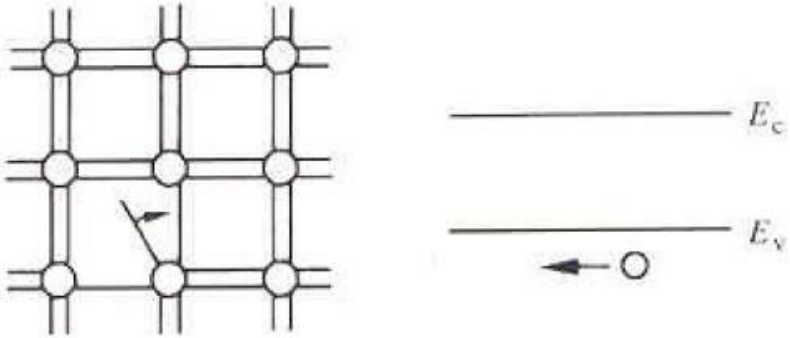


(a) No carriers





(b) The electron



(c) The hole

Donors and Acceptors

Pure semiconductor material (*intrinsic* semiconductor)

each electron excited into the conduction band leaves a vacant state in the valence band

The number of negatively charged electrons ***n*** in the conduction band
= the number of positively charged holes ***p*** in the valence band

n_i : the densities of electrons (carriers cm^{-3})
p_i : the densities of holes (carriers cm^{-3})

subscript "*i*" means *intrinsic*

→The most useful means for controlling the number of carriers in a semiconductor is by incorporating *substitutional impurities;* that is, impurities that occupy lattice sites in place of the atoms of the pure semiconductor

Donors and Acceptors

Donors

substitutional group V impurities *donate electrons to the silicon*

if we replace one silicon atom (four valence electrons) with an impurity atom from group V in the periodic table, such as phosphorus (five valence electrons), then four of the valence electrons from the impurity atom fill bonds between the impurity atom and the adjacent silicon atoms.

The fifth electron, however, is not covalently bonded to its neighbors; it is only weakly bound to the impurity atom by the excess positive charge on the nucleus.

→ Only a small amount of energy is required to break this weak bond so its the fifth electron can wander about the crystal and contribute to electrical conduction.

Donors and Acceptors

Types of Dopants in Extrinsic Semiconductors

Doping : impurities that occupy lattice sites in place of the atoms of the pure semiconductor

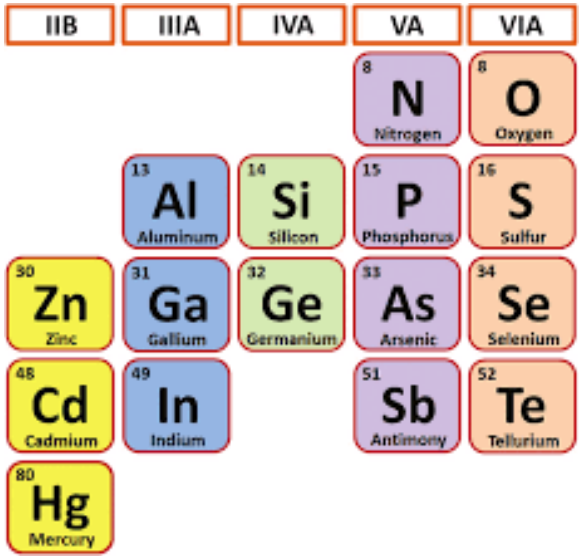
Crystals of Silicon and Germanium are doped using two types of dopants:

Pentavalent (valency 5)

; Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

Trivalent (valency 3);

Indium (In), Boron (B), Aluminum (Al), etc.



Donors and Acceptors

Donors

the amount of energy needed to break the bond to a donor atom,

The energy binding the electron to the core

$$E = \frac{m_n^* q^4}{8h^2\epsilon_0^2\epsilon_r^2} = \frac{13.6}{\epsilon_r^2}\frac{m_n^*}{m_0}\text{ eV}$$

where ε_r is the relative permittivity of the semiconductor and m_n^* is the effective mass of the electron in the semiconductor conduction band

For silicon with ε_r =11.7 and m_n^* = 0.26 m_o, E = 0.03 eV, which is only about 3% of the silicon bandgap energy (1.1 eV)

More detailed calculations and measurements indicate that the binding energy for typical donors is somewhat higher: 0.044 eV for phosphorus, 0.049 eV for arsenic, and 0.039 eV for antimony

→ much easier to break the weak bond connecting the fifth electron to the donor than to break the silicon-silicon bonds.

Donors and Acceptors

N-type semiconductor

According to the energy-band model, it requires only a small amount of energy to excite the electron from the donor atom into the conduction band, while a much greater amount of energy is required to excite an electron from the valence band to the conduction band

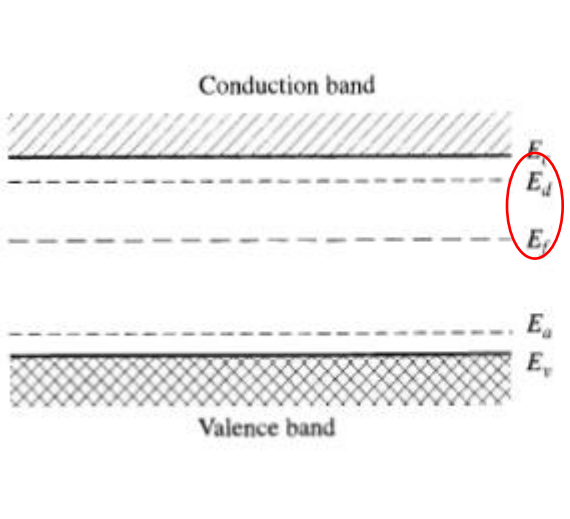


FIGURE 1.6 Energy-band diagram for a semiconductor showing the lower edge of the conduction band E_c, a donor level E_d within the forbidden gap, the Fermi level E_f, an acceptor level E_a, and the top edge of the valence band E_v.

the state corresponding to the electron when bound to the donor atom by a level E_d about 0.05 eV below the bottom of the conduction band E_c

The density of donors (atoms cm^{-3}); N_d

Donors and Acceptors

N-type semiconductor

Most impurities are of the donor type

→ the number of electrons in the conduction band is much greater than the number of holes in the valence band

Electron: *majority carriers*

Holes: *minority carrier*

n-type semiconductor; because most of the current is carried by the *negatively charged* electrons.

Donors and Acceptors

Conduction electron concentration vs. temperature (N-type semiconductor)

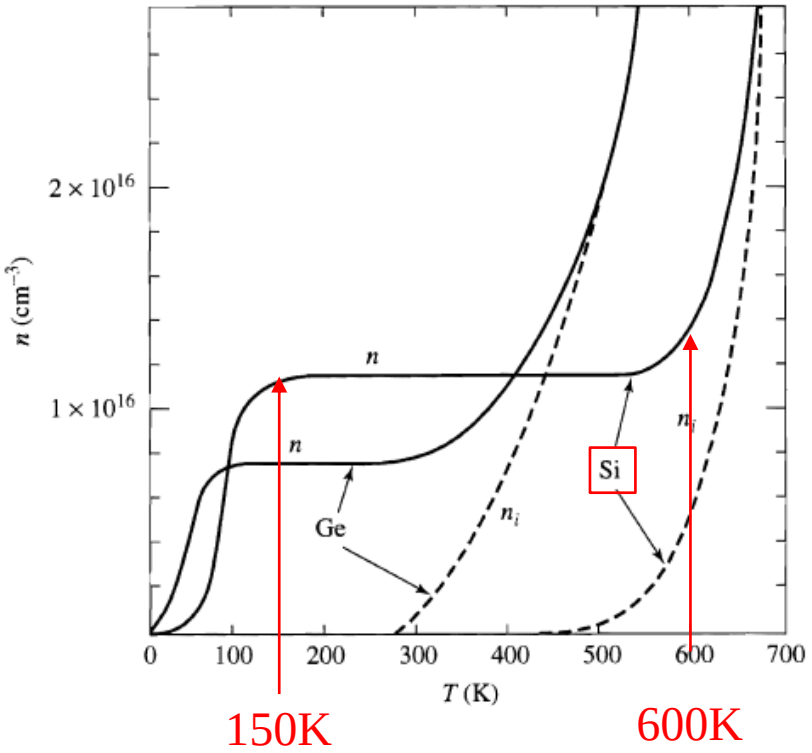


FIGURE 1.9 Electron concentration versus temperature for two *n*-type doped semiconductors: (*a*) Silicon doped with 1.15×10^{16} arsenic atoms cm^{-3}[1], (*b*) Germanium doped with 7.5×10^{15} arsenic atoms cm^{-3}[2].

the hole density is at most equal to n_i

n_i : the densities of electrons (carriers cm^{-3})

Electrons are far more numerous than holes
when the temperature is in the range sufficient to ionize the donor atoms (about 150 K)
but not adequate to free many electrons from silicon-silicon bonds (about 600 K).

Donors and Acceptors

p-type semiconductor

Similarly, an impurity atom with three valence electrons, such as boron, can replace a silicon atom in the lattice.

→ The three electrons fill three of the four covalent silicon bonds, leaving one bond vacant

→ If another electron moves to fill this vacant bond from a nearby bond, the vacant bond is moved, carrying with it positive charge and contributing to hole conduction

Just as a small amount of energy was necessary to initiate the conduction process in the case of a donor atom, only a small amount of energy is needed to excite an electron from the valence band into the vacant bond caused by the trivalent impurity

Donors and Acceptors

p-type semiconductor

This energy is represented by an energy level E_a slightly above the top of the valence band E_v

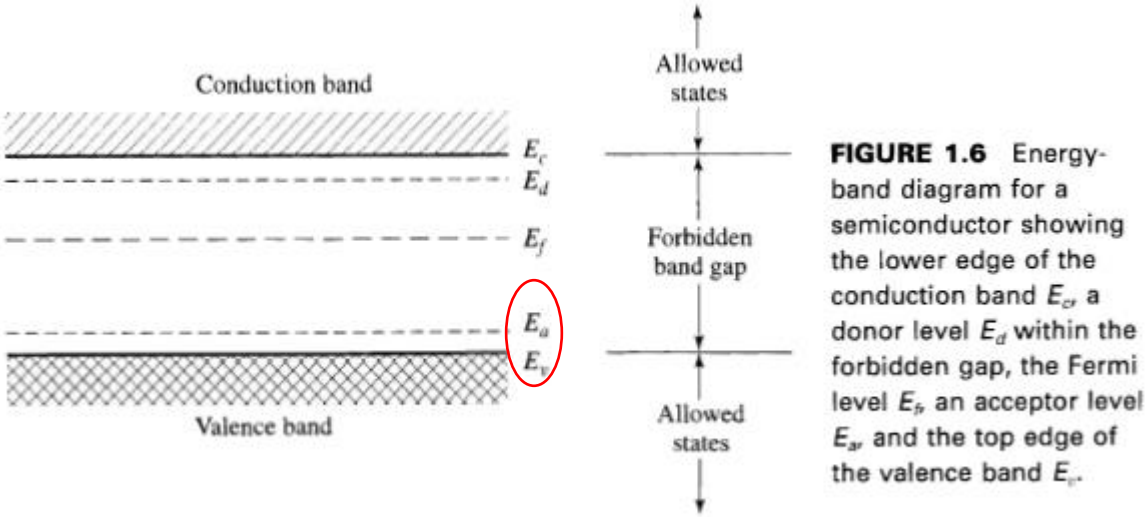


FIGURE 1.6 Energy-band diagram for a semiconductor showing the lower edge of the conduction band E_c, a donor level E_d within the forbidden gap, the Fermi level E_f, an acceptor level E_a, and the top edge of the valence band E_v.

An impurity that contributes to hole conduction is called an *acceptor impurity* because it leads to vacant bonds, which easily accept electrons. The acceptor concentration (atoms cm^{-3}) is denoted as N_a.

If most of the impurities in the solid are acceptors, the material is called a *p-type* semiconductor because most of the conduction is carried by *positively charged* holes.

Donors and Acceptors

p-type semiconductor

Semiconductors in which conduction results primarily from carriers contributed by impurity atoms are said to be *extrinsic*.

→The donor and acceptor impurity atoms, which are intentionally introduced to change the charge-carrier concentration, are called *dopant* atoms.

Donors and Acceptors

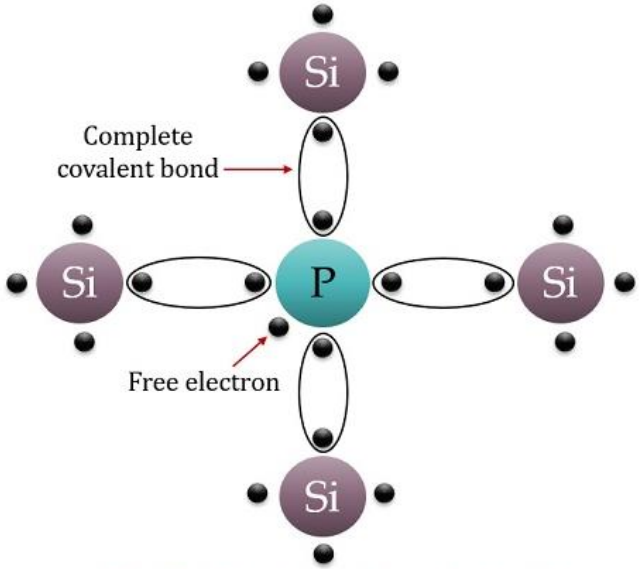
Comparison Chart

Parameter	P-Type	N-Type
Impurity doped	Trivalent impurity	Pentavalent impurity
Also known as	Acceptor atom because of presence of additional hole.	Donor atom due to the existence of additional electron.
Doped group	Group III elements. For eg - boron, gallium, indium, aluminium etc.	Group V elements. for eg - arsenic, antimony, bismuth, phosphorus etc.
Majority carriers	Holes	Electrons
Minority carriers	Electrons	Holes
Conductivity	Due to presence of holes.	Due to presence of electrons.
Presence of fermi level	Fermi level appears closer to the valence than the conduction band.	Fermi level is present nearer to the conduction band than the valence band.
Concentration of electrons	Low	Very high as compared to p type semiconductor
Concentration of holes	High	Comparatively less than p type semiconductor.

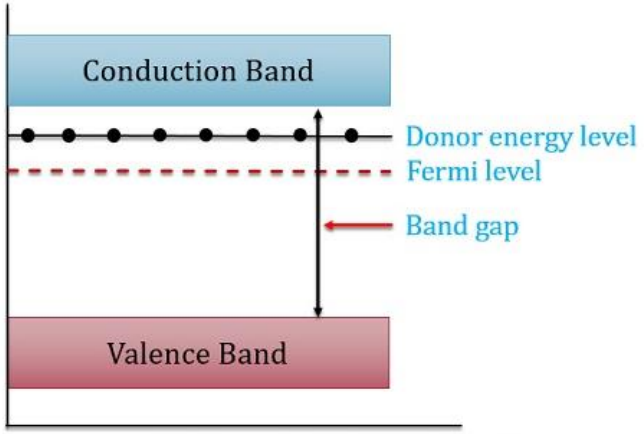
Donors and Acceptors

n-type semiconductor

N-type extrinsic semiconductors are formed when group V elements like phosphorus, antimony, bismuth etc. are doped to a pure semiconductor crystal.



- Si = Intrinsic semiconductor atom
- P = Pentavalent impurity atom

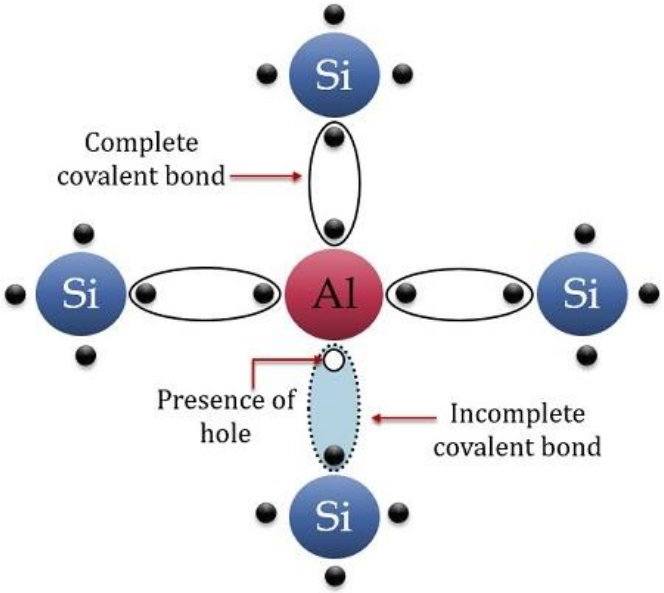


Energy level diagram of
N type semiconductor

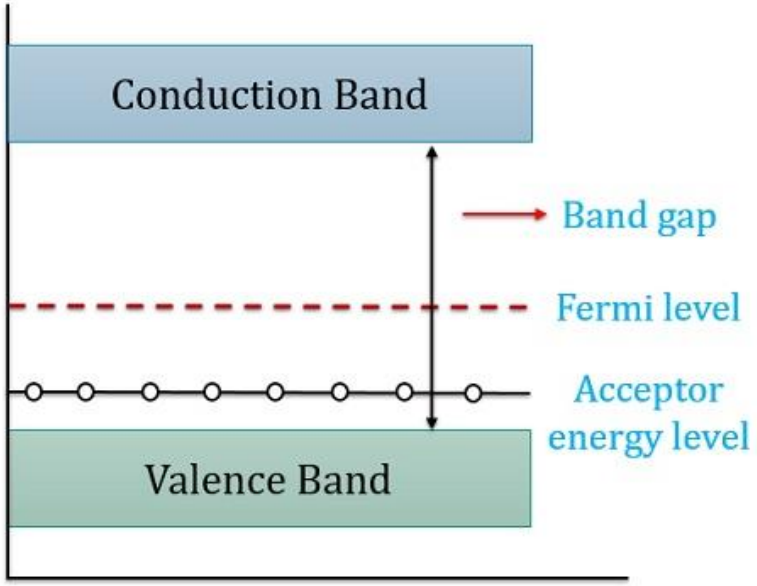
Donors and Acceptors

P-type semiconductor

When a pure or intrinsic semiconductor is doped with group III elements of periodic table like **boron, gallium, aluminium** etc. that these are known as the p-type extrinsic semiconductor.



- Si = Intrinsic semiconductor atom
- Al = Trivalent impurity atom



Energy level diagram of P type semiconductor

Donors and Acceptors

Key Differences between P-Type and N-Type Semiconductor

1. A p-type semiconductor is formed when **group III** elements are doped to a pure semiconductor material. As against, an n-type semiconductor is formed when **group V** elements are doped to an intrinsic semiconductor.

2. As elements like boron, gallium, indium etc. are doped to form p-type semiconductor thus it produces an additional hole hence also known as **acceptor atom**.
   On the contrary, elements like arsenic, antimony, bismuth etc. are doped in order to have n-type semiconductor hence it produces an additional electron thus also termed as **donor atom**.

3. Another factor that generates a key difference between p-type and n-type semiconductor is that in case of p-type semiconductor holes are the majority carriers. While in case of n-type semiconductor electrons act as majority carriers.

4. The minority carriers in case of the p-type semiconductor are electrons whereas in that of n-type semiconductor these are holes.

Donors and Acceptors

Key Differences between P-Type and N-Type Semiconductor

5. As we know that the conductivity of the device depends on the majority carriers. Thus in the p-type semiconductor, **holes are responsible for current conduction**. On the contrary, in case of an n-type semiconductor, **electrons are responsible for current conduction**.

6. The **fermi-level** in case of p-type semiconductor appears closer to valence band than that of the conduction band. As against, the Fermi level in case of n-type semiconductor exists near the conduction band.

7. The concentration of holes is more than electrons in case of p-type semiconductor material. While in n-type semiconductors the concentration of electrons is greater than holes.

Donors and Acceptors

Compensation

The intentional doping of silicon with shallow donor impurities

➡ *n*-type

The intentional doping of silicon with shallow acceptor impurities

➡ *p*-type

An especially useful feature of the doping process is that one may *compensate* a doped silicon crystal (for example an *n*-type sample) by subsequently adding the opposite type of dopant impurity (a *p*-type dopant in this example).

Donors and Acceptors

Compensation

As donor atoms add allowed energy states to the energy-band diagram at E_d, close to the conduction band energy E_c, whereas acceptor atoms add allowed energy states at E_a, close to the valence-band energy E_v

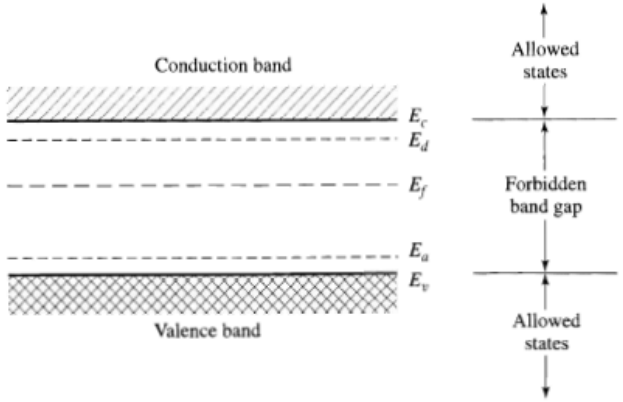


FIGURE 1.6 Energy-band diagram for a semiconductor showing the lower edge of the conduction band E_c, a donor level E_d within the forbidden gap, the Fermi level E_f, an acceptor level E_a, and the top edge of the valence band E_v.

At typically useful temperatures for silicon devices, each donor atom has lost an electron and each acceptor atom has gained an electron

Because the acceptor atoms provide states at lower energies than those either in the conduction band or at the donor levels, the electrons from the donor levels transfer (or "fall") to the lower-energy acceptor sites as long as any of these remain unfilled.
Hence, in a doped semiconductor, the effective dopant concentration is equal to the magnitude of the difference between the donor and acceptor concentrations $|N_d - N_a|$;

- the semiconductor is n-type if N_d exceeds N_a and *p-type* if N_a exceeds N_d.

Theoretically, one can achieve a zero effective dopant density through compensation (with $N_d = N_a$),

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