PHYS389: Semiconductor Applications

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- **Semiconductor Physics**
  - Lattice structure
  - Electrons in semiconductors
  - Doping
- **Semiconductor Applications**
  - P-N Junctions
  - Field Effect Transistors
  - Integrated circuits
- **Applications in Nuclear and Particle Physics**
  - Accelerators and Nuclear Reactions
  - Nuclear radiation detection
    - Range of charged particles
    - Silicon and Germanium radiation detectors
    - Tracking

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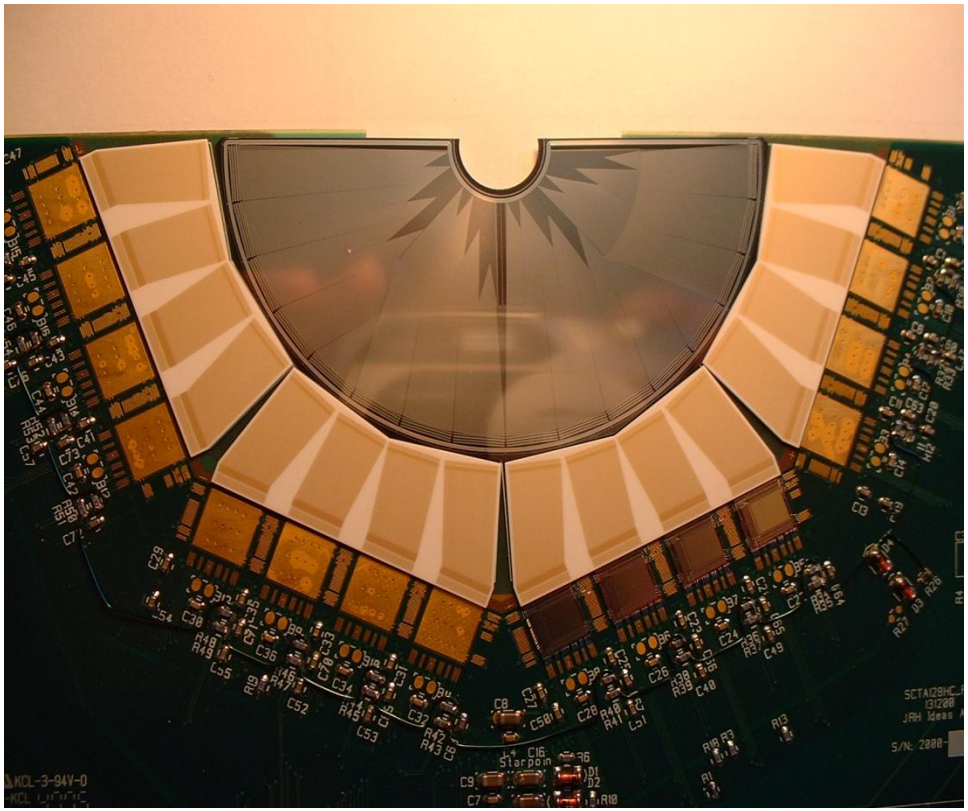
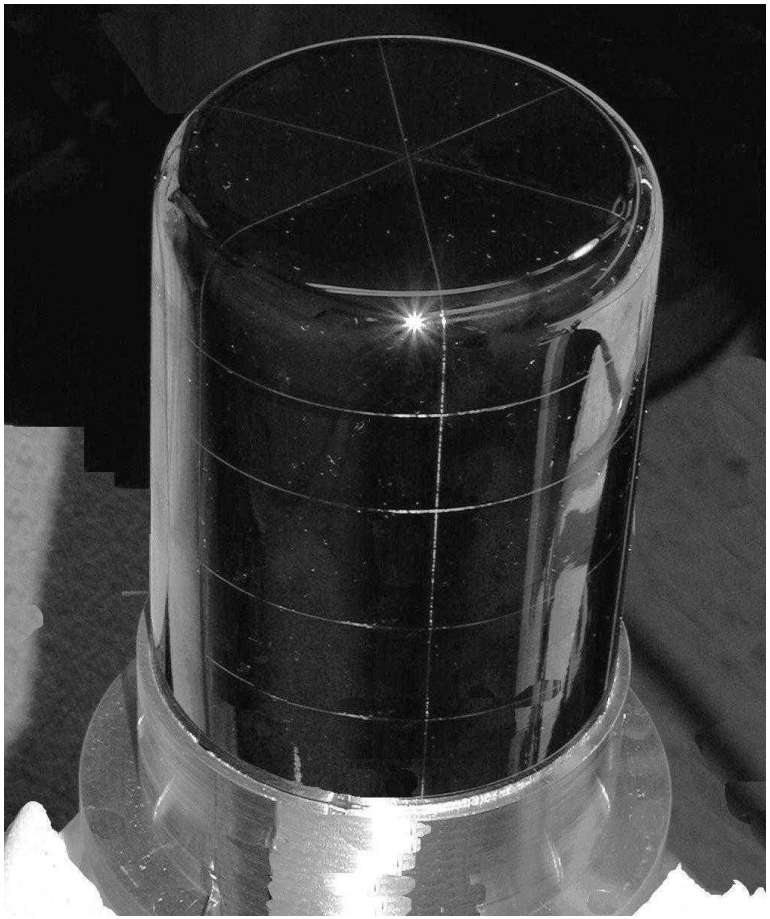
Semiconductor Research at Liverpool



- LHCb Silicon tracker

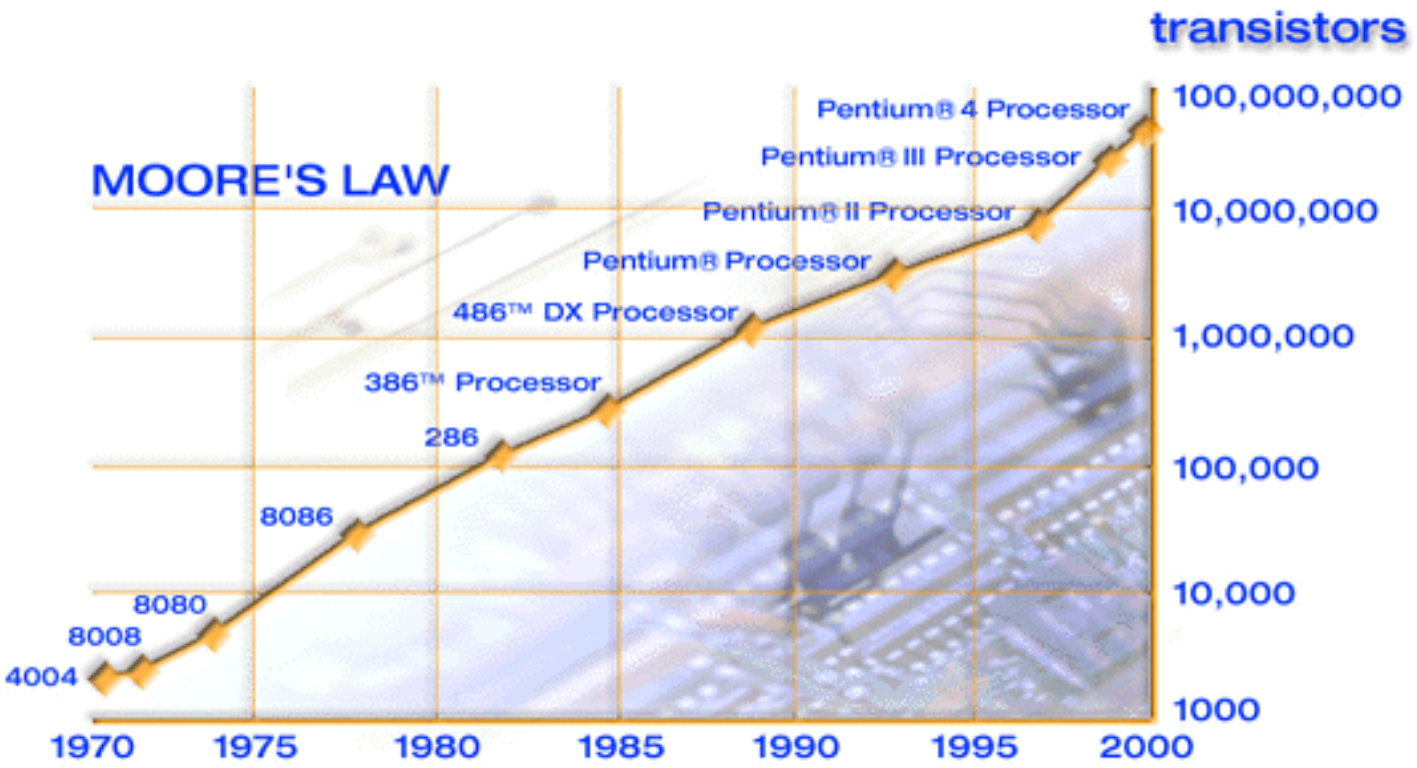
- Germanium imaging detector



Lecture 1: What are Semiconductors?

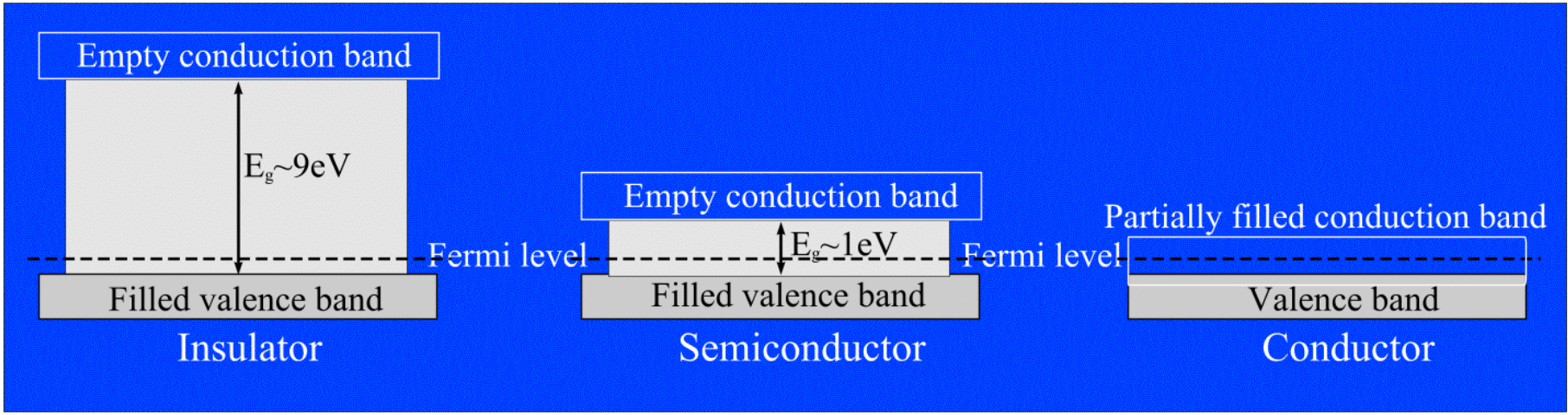
- History
- Why all the fuss?
- Crystal structure
- Energy Bands
- Density of states
- Fermi Level
- The Maxwell-Boltzmann approximation

Moore's Law



- "The number of transistors per integrated circuit will double every 18 months", Gordon Moore, 1965.

What is a semiconductor?



- When an allowed band is completely filled with electrons, the electrons in the band cannot conduct any current.
- Metals have a high conductivity because of the large number of electrons that can participate in current transport
- Semiconductors have zero conductivity at 0K.

Semiconductors: Classification

Period	Column II	III	IV	V	VI
2		B	C	N	
		Boron	Carbon	Nitrogen	
3	Mg	Al	Si	P	S
	Magnesium	Aluminium	Silicon	Phosphorus	Sulphur
4	Zn	Ga	Ge	As	Se
	Zinc	Gallium	Germanium	Arsenic	Selenium
5	Cd	In	Sn	Sb	Te
	Cadmium	Indium	Tin	Antimony	Tellurium
6	Hg		Pb		
	Mercury		Lead		

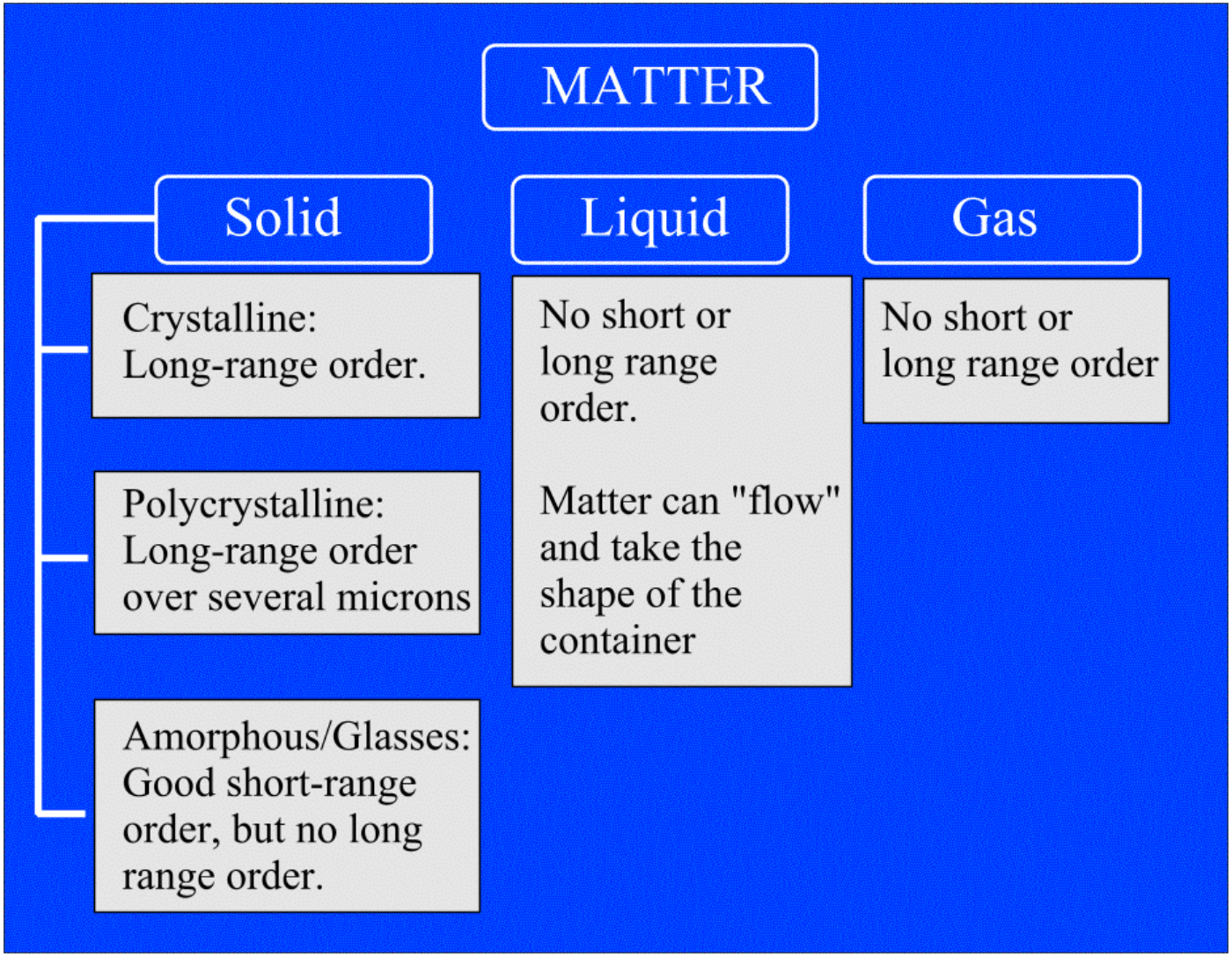
Semiconductors composed of a single species of atoms, such as silicon and germanium are found in column IV of the periodic table. They are often termed **elemental** semiconductors.

Compound semiconductors are composed of two or more elements. For example, GaAs, AlSb and InSb are all III-V semiconductors. CdS, CdTe and ZnTe are all II-VI.

Why all the fuss?

- Semiconductors have special properties that allow you to alter their **conductivities** from very low to very high values.
- Charge transport in semiconductors can occur by two different kinds of particles – **electrons** and **holes**.
- Semiconductor devices can be designed that have input-output relations to produce **rectifying** properties; inverters and amplifiers.
- Semiconductor devices can be combined with other elements (resistors, capacitors etc) to produce circuits on which modern information-processing chips are based.

The different states of matter



The crystal lattice

- The periodic arrangement of atoms in a crystal is called a **lattice**.
- The lattice by itself is a mathematical abstraction.
- A building block of atoms called the **basis** is then attached to each lattice point, yielding a crystal structure.
- For a given semiconductor there is a basis that is representative of the entire lattice.
- In a crystal an atom never strays far from a single fixed position.
- The thermal vibrations associated with the atom are centred about this position.

Lattice + Basis = Crystal Structure

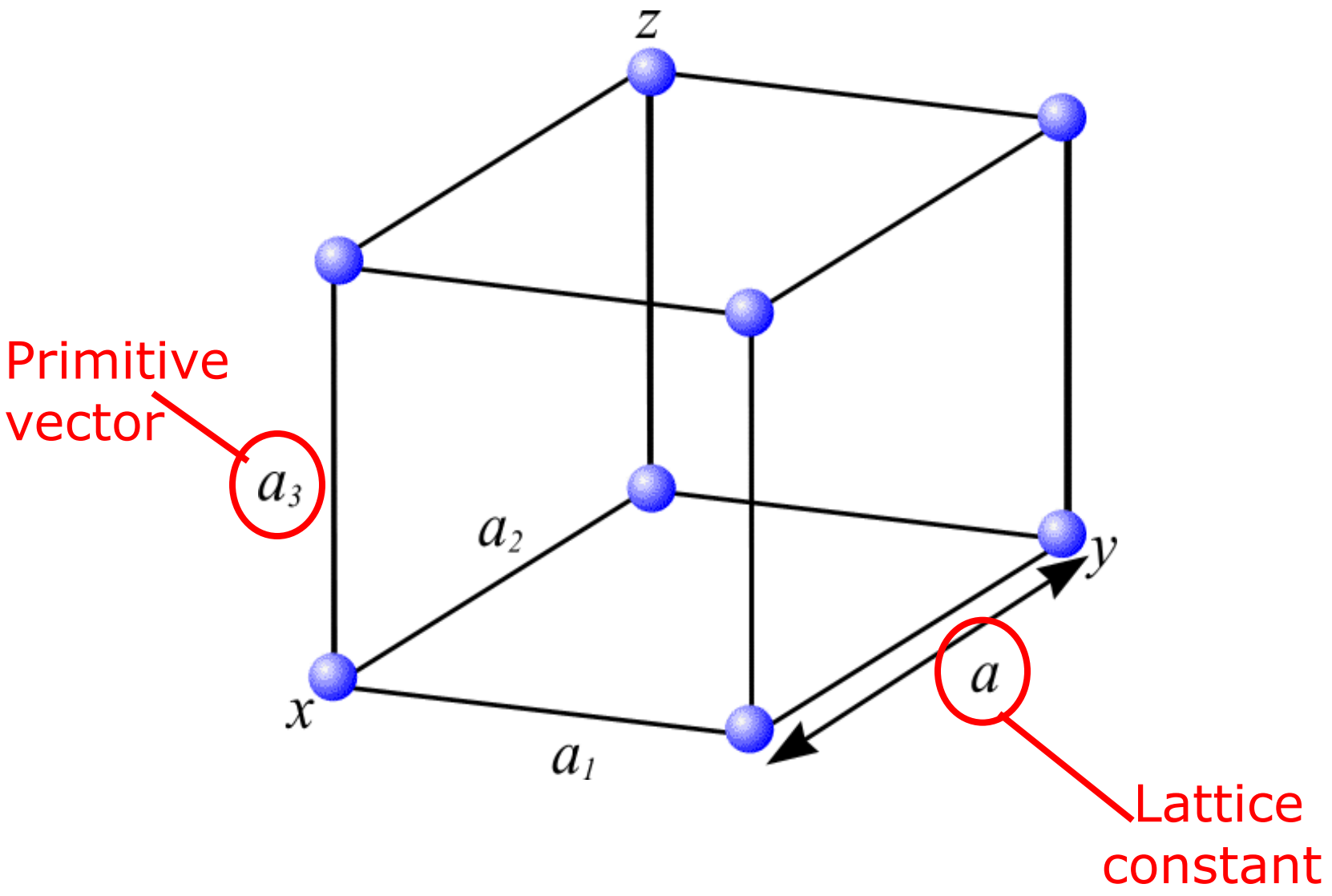
The crystal lattice

- An important property of a lattice is the ability to define three vectors ***a*₁**, ***a*₂** and ***a*₃** such that any lattice point ***R'*** can be obtained from any other lattice point ***R*** by a translation:

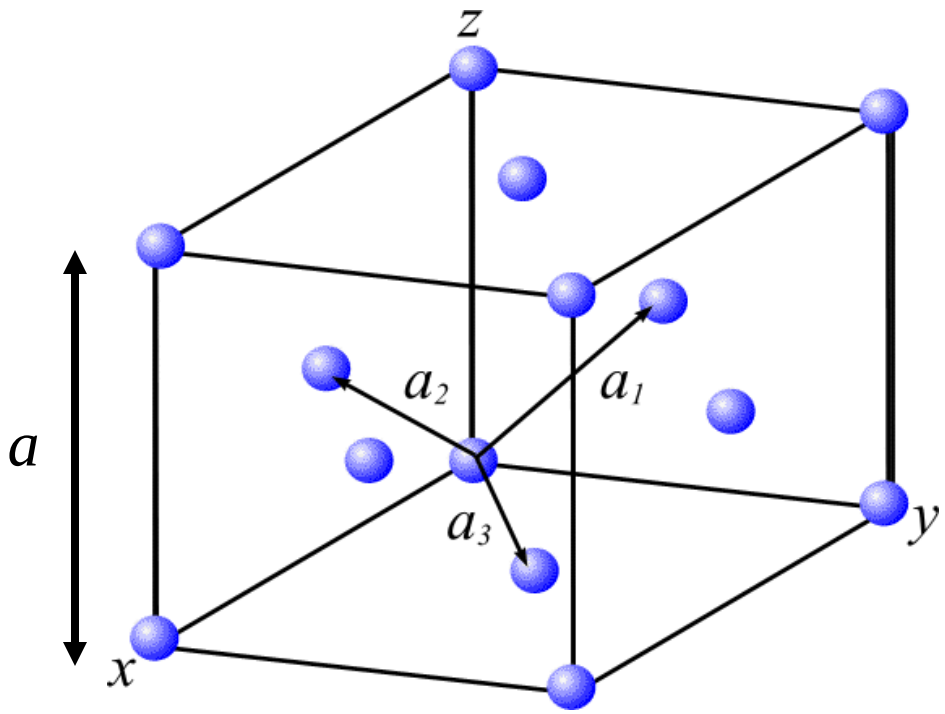
$$R' = R + m_1 a_1 + m_2 a_2 + m_3 a_3$$

- m_1, m_2 and m_3 are integers. Such a lattice is called a Bravais lattice.
- a_1, a_2 and a_3 are termed the **primitive** if the volume of the cell formed by them is the smallest possible.
- Various kinds of lattice structures are possible in nature.
- We will concentrate on the cubic lattice.

The Cubic Lattice Structure



Face Centred Cubic lattice structure



- The Face Centred Cubic (FCC) lattice is the most important for semiconductors.
- A symmetric set of primitive vectors:

$$a_1 = \frac{a}{2}(\hat{y} + \hat{z}),\ a_2 = \frac{a}{2}(\hat{z} + \hat{x}),\ a_2 = \frac{a}{2}(\hat{x} + \hat{y})$$

The Lattice Constant

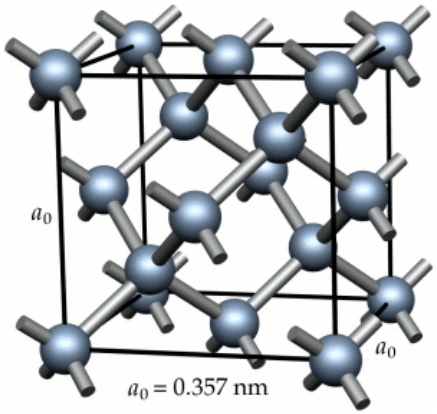
Semiconductor lattices

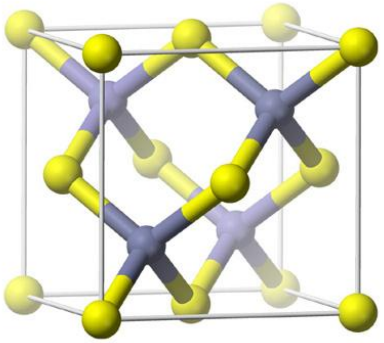
- Essentially all semiconductors of interest for electronics and opto-electronics have an underlying FCC lattice structure.
- However, they have two atoms per basis:

$$(000) \text{ and } \left(\frac{a}{4}, \frac{a}{4}, \frac{a}{4}\right)$$

- This can be seen as two interpenetrating FCC sub-lattices with one sub-lattice displaced from the other by one quarter of the distance along a diagonal of the cube.
- The separation between the atoms is $\sqrt{3}a/4$.
- If the two atoms of the basis are the same, the structure is called **diamond**, semiconductors such as silicon and germanium fall into this category.
- If the two atoms are different, the structure is called **zinc blende**, example III-V semiconductors include GaAs and AlAs.

Diamond

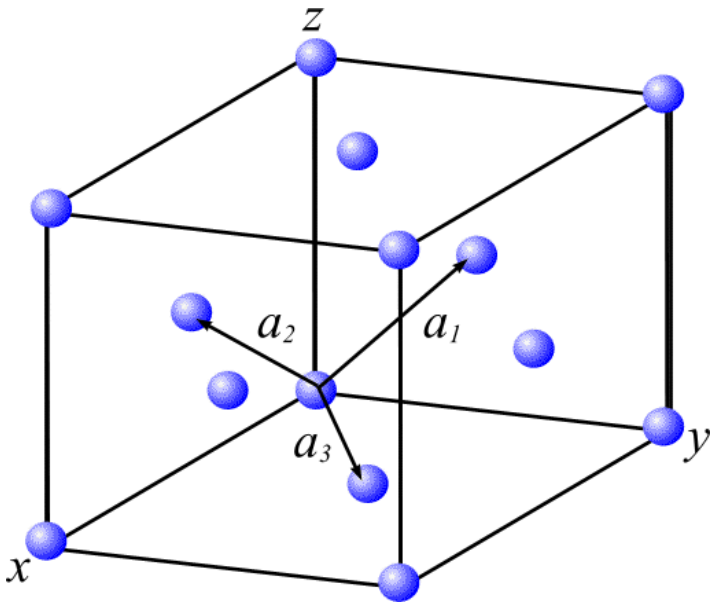




Zinc blende

Semiconductor example

- At 300K the lattice constant for silicon is 0.543nm. Suppose we want to calculate the number of silicon atoms per cubic centimetre.



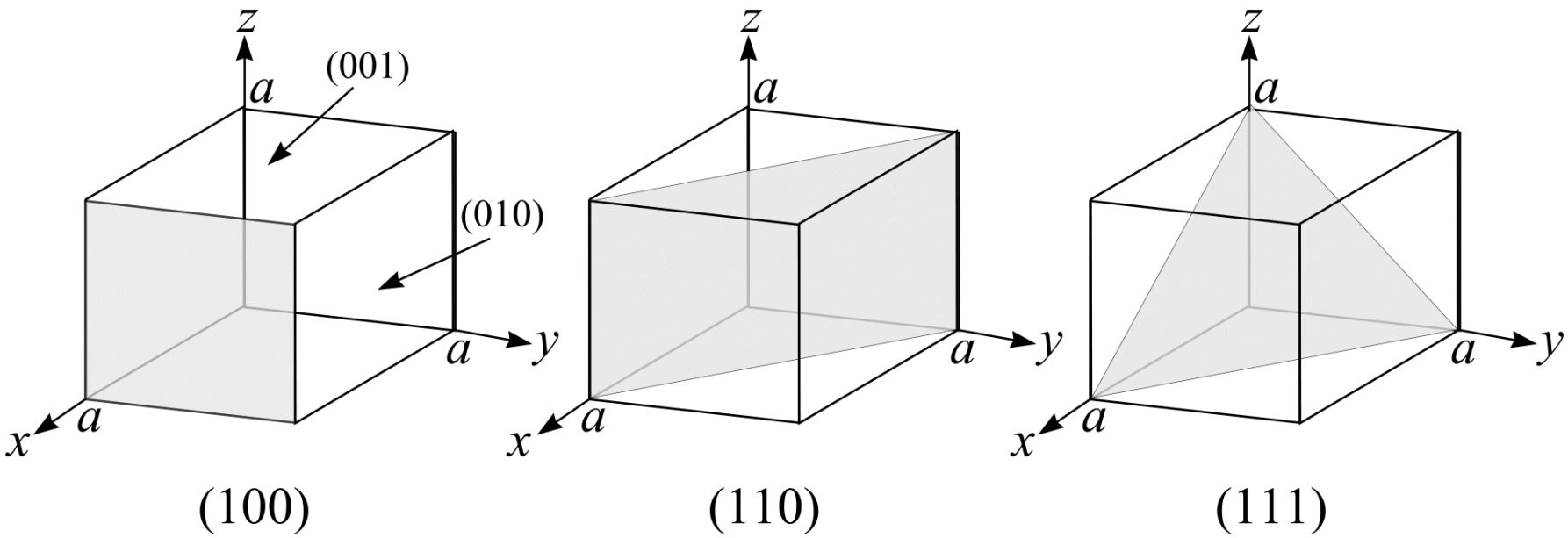
- There are 8 atoms per unit cell, therefore:

$$N_{si} = \frac{8}{a^3} = \frac{8}{(5.43\times10^{-8})^3} = 5\times10^{22}\ \text{atoms/cm}^3$$

Semiconductor lattice properties

- We need a convenient method of defining the various planes – **Miller Indices**.
  - Define the *x, y, z* axes.
  - Take intercepts of the plane along the axes in units of lattice constants
  - Take the reciprocal of the intercepts and reduce them to the smallest integers *h, k* and *l*.
- (hkl) denotes a family of parallel planes.
- {hkl} denotes a family of equivalent planes. For example {100}, {010} and {001} are all equivalent in the cubic structure.
- [hkl] denotes a crystal direction e.g. [100] x-axis
- <hkl> denotes a full set of equivalent directions.

Miller Indices



So what does this mean?

The crystal properties along different planes are different – there are differences in the atomic spacings.

This means **electrical** and other device properties are dependent on the crystal orientation.

Electrons in free space

- Electrons inside semiconductors can be regarded as "free" under proper conditions – allowing rules for free electrons to be easily adapted for semiconductors.
- Solving Schrödinger equation:

$$\left[-\frac{\hbar^2}{2m_0}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)+V_0\right]\psi(r)=E\psi(r)$$

- The energy of the electron is obtained as:

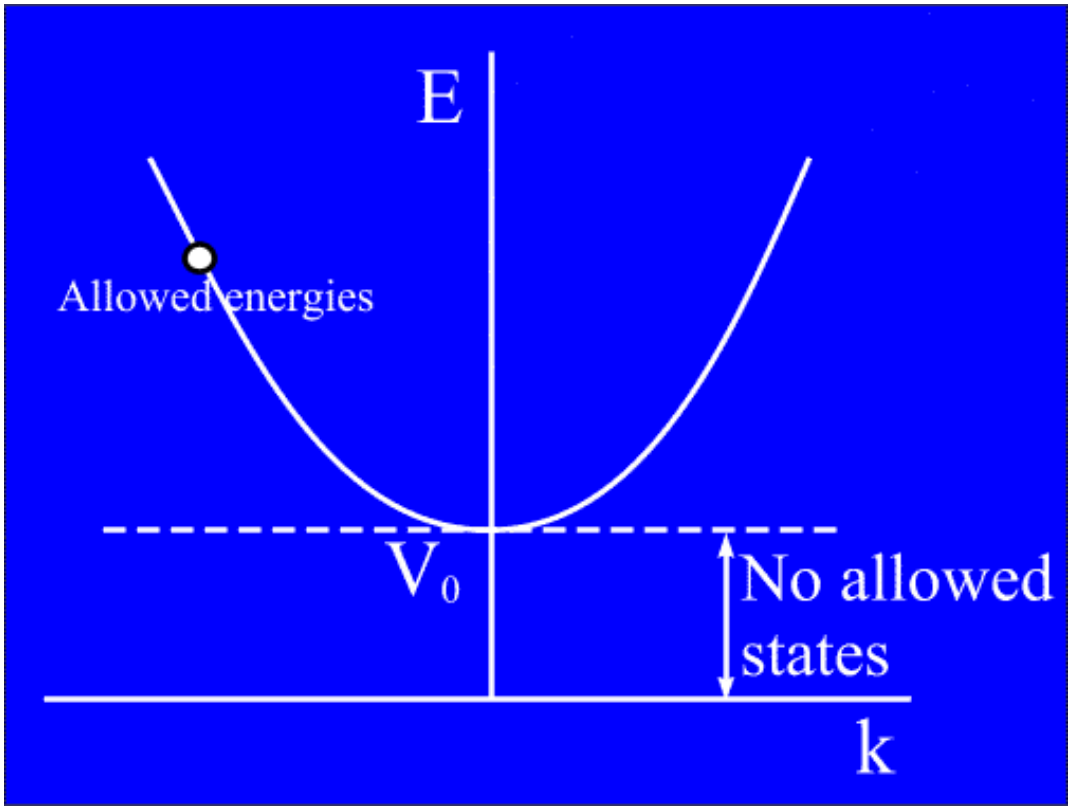
$$E=\frac{\hbar^2k^2}{2m_0}+V_0 \qquad \text{Classically: } E=\frac{p^2}{2m_0}$$

- And the momentum is obtained as: $p=\hbar k$
- Equation of motion: $\hbar\frac{dk}{dt}=F_{ext}$
- Where *k* is the wavevector: $k=\frac{2\pi}{\lambda}$

- The energy-momentum (E-k) relation for free electrons now be obtained.

Electrons in free space E-k relation

- The energy-momentum relationship:

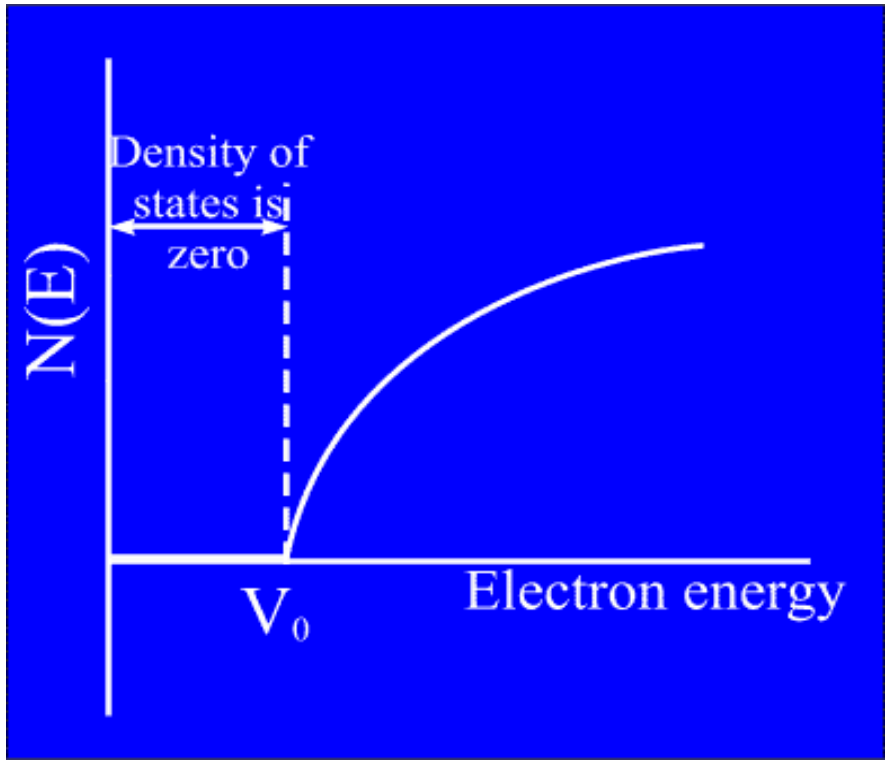


- The allowed energies form a **continuous** band.

The density of states

- The density of states is the number of available electronic states per unit volume per unit energy around an energy *E*.
- Is a very important, and important physical phenomena such as optical absorption and transport are intimately dependent on this concept.
- The density of states *N(E)* can be written as:

$$N(E) = \frac{\sqrt{2} m_0^{3/2} (E - V_0)^{1/2}}{\pi^2 \hbar^3}$$



Density of states: Example

- The density of states of electrons moving in zero potential at an energy of 0.1eV:

$$N(E) = \frac{\sqrt{2}m_0^{3/2}E^{1/2}}{\pi^2\hbar^3}$$

$$= \frac{\sqrt{2}(0.91\times10^{-30}\text{kg})^{3/2}(E^{1/2})}{\pi^2(1.05\times10^{-34}\text{Js})^3}$$

$$= 1.07\times10^{56}E^{1/2}\text{J}^{-1}\text{m}^{-1}$$

- Expressed in the more commonly used units of $eV^{-1}cm^{-3}$ gives,

$$N(E) = 2.15\times10^{21}\text{eV}^{-1}\text{cm}^{-3}$$

Electrons in crystalline solids

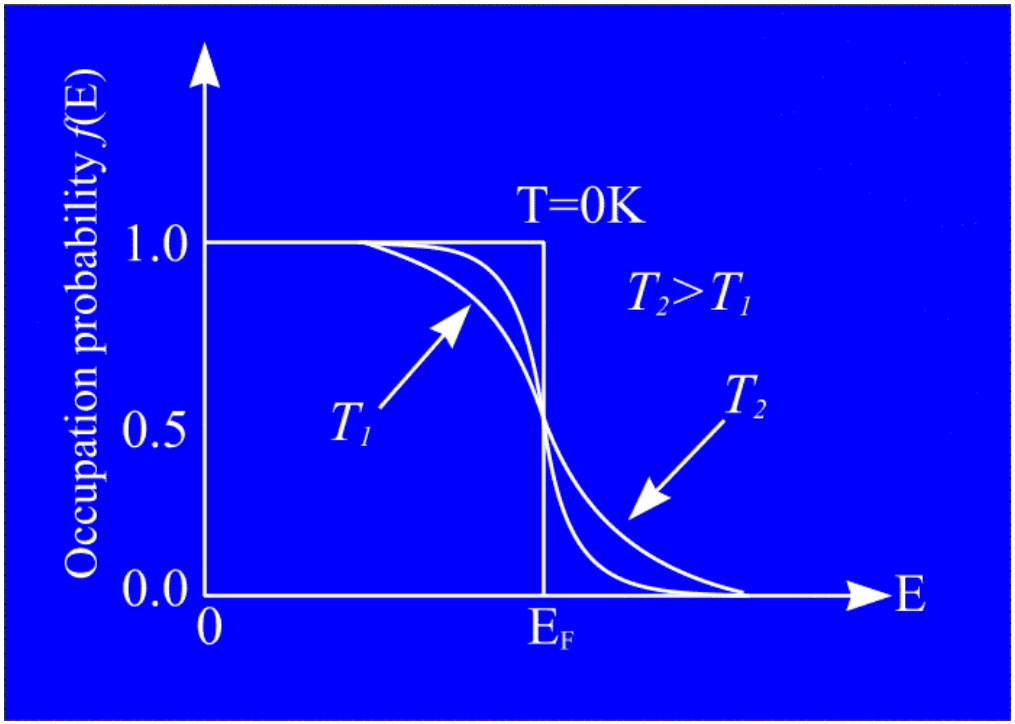
- When the electron wavefunction is confined to ~10nm around the nucleus, only discrete or bound state energies are allowed.
- When the atomic spacing becomes 10-20nm, electrons will sense the neighbouring nuclei, and will be influenced by them.
- The result of these interactions is:
  - Lower-energy core levels remain relatively unaffected
  - Electronic levels with higher energies and whose wavefunctions are not confined to the nucleus, broaden into bands of allowed energies.
  - These allowed bands are separated by **bandgaps**.
- Within each band the electron is described by a k-vector (as before), only the relation is more complicated.
- The electron behaves as if it were in free space, except it responds as if it had a different or **effective** mass.

Filling of electronic states

- How do the electrons distribute themselves among the various allowed electronic states?
- The distribution function *f(E)* tells us the probability that an allowed level at energy *E* is occupied.
- Is the Maxwell-Boltzmann distribution function :

$$F(E) = \exp -\left(\frac{E - E_F}{k_B T}\right)$$

- E_F is the Fermi level representing the energy where $F(E_F) = 1/2$.



The Fermi level in semiconductors

- If the electron density is small, so that *F(E)* is always small. The Fermi function can be presented by the Boltzmann function.
- The electron density can now be analytically evaluated as:

$$n = \int_{E_0}^{\infty} N(E)F(E)dE$$

$$= N_C \exp\left(\frac{E_F - E_0}{k_B T}\right)$$

- Where N_c is called the effective density of states and is defined as:

$$N_C = 2\left(\frac{m_0}{2\pi\hbar^2}\right)^{3/2}(k_B T)^{3/2}$$

Fermi level: Example calculation

- Calculate the Fermi level at 77K for a case where the electron density is $10^{19}cm^{-3}$. Assume the energy band starts at *E=0.*
- In the Boltzmann approximation, the Fermi level is:

$$E_F = k_B T \ln\left(\frac{n}{N_c}\right)$$

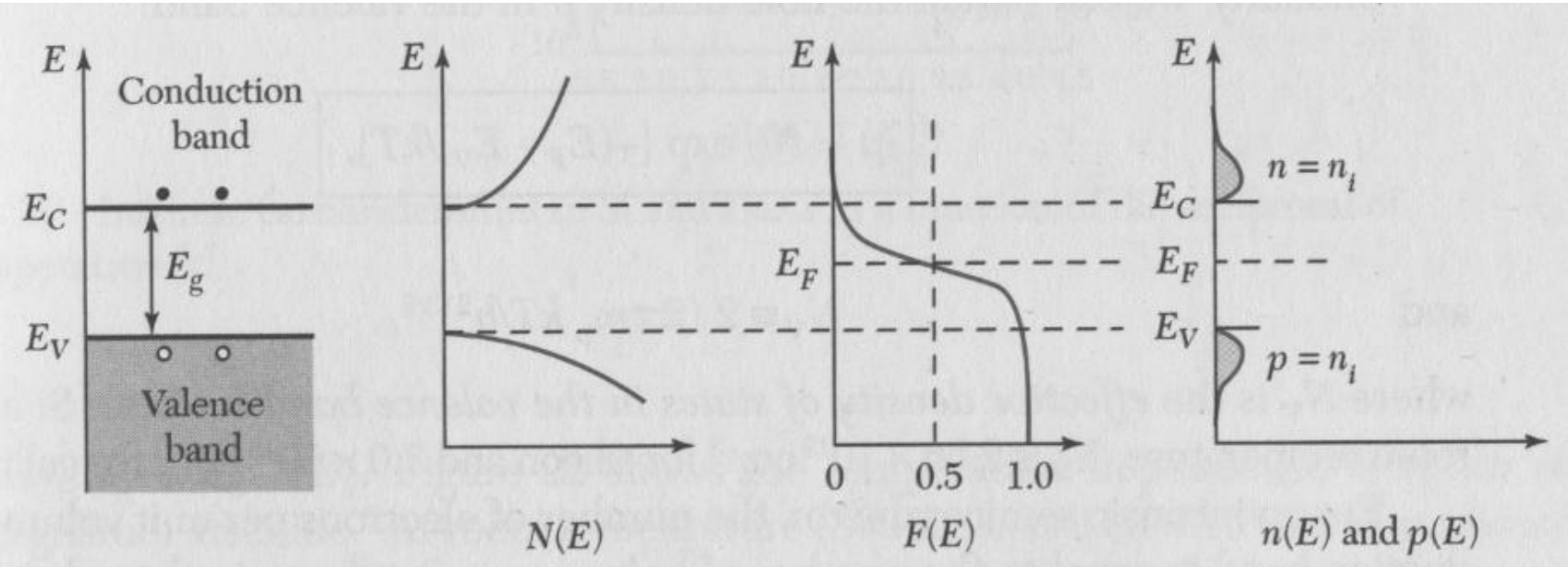
$$N_C = 3.34 \times 10^{18} cm^{-3}$$

$$E_F = 0.0067\left[\ln\left(\frac{10^{19}}{3.34 \times 10^{18}}\right)\right] = 7.35meV$$

Summary of Lecture 1

Semiconductor band diagram

Fermi distribution function



Density of states

Carrier concentration

$$n = \int_{E_C}^{\infty} N(E)F(E)dE$$