BENHA UNIVERSITY
FACULTY OF ENGINEERING (SHOUBRA)
ELECTRONICS AND COMMUNICATIONS ENGINEERING

CCE 201
Solid State Electronic Devices
(2022 - 2023) term 231

Lecture 2: Semiconductor Physics (part 2).

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Outlines

- Extrinsic Material.
- The Fermi – Dirac distribution function
- Carrier concentration.
- n-type semiconductors.
- p-type semiconductors
- Summary.

Extrinsic Material:

- Another way to increase the number of charge carriers is to add them in from an external source.
- Doping or implant is the term given to a process whereby one element is injected with atoms of another element in order to change its properties.
- Semiconductors (Si or Ge) are typically doped with elements such as Boron, Arsenic and Phosphorous to change and enhance their electrical properties.
- By doping, a crystal can be altered so that it has a predominance of either electrons or holes.
- Thus, there are two types of doped semiconductors, n-type (mostly electrons) and p-type (mostly holes).
- When a crystal is doped such that the equilibrium carrier concentrations n_0 and p_0 are different from the intrinsic carrier concentration n_i, the material is said to be extrinsic.

Donor impurities (elements of group V): P, Sb, As
Acceptor elements (group III): B, Al, Ga, In

Total number of electrons

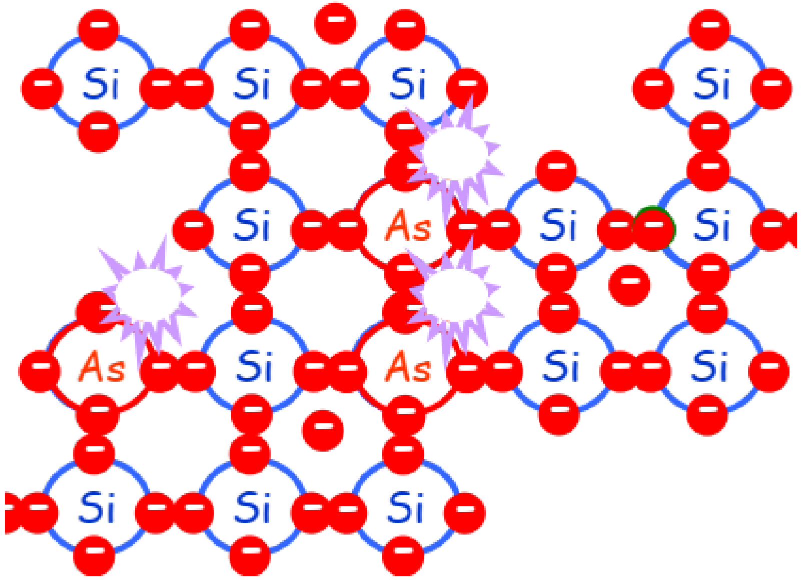
III – Al – 13

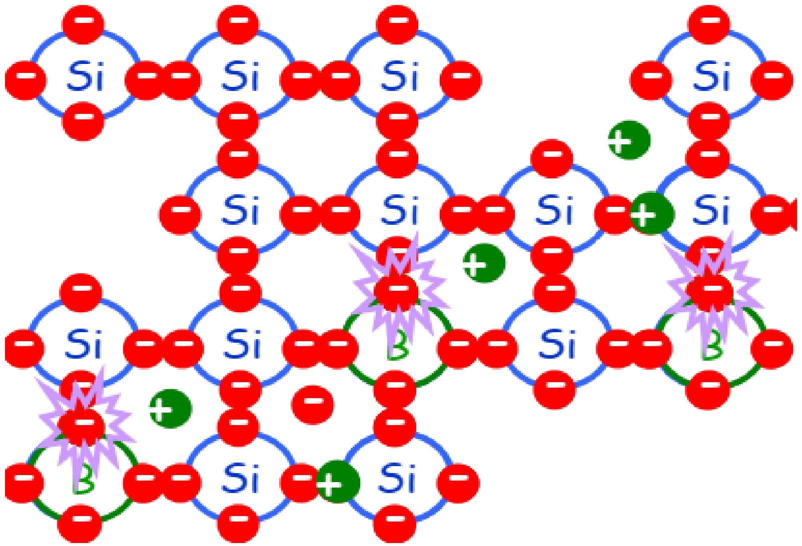
IV – Si – 14

V - P - 15

Extrinsic Material:

- Inject Arsenic into the crystal with an implant step.
- Arsenic is Group5 element with 5 electrons in its outer shell, (one more than silicon).
- This introduces extra electrons into the lattice which can be released through the application of heat and so produces and electron current.
- The result here is an n-type semiconductor (n for negative current carrier).
- Inject Boron into the crystal with an implant step.
- Boron is Group3 element is has 3 electrons in its outer shell (one less than silicon)
- This introduces holes into the lattice which can be made mobile by applying heat. This gives us a hole current.
- The result is a P-type semiconductor (p for positive current carrier)





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The Fermi – Dirac distribution function:

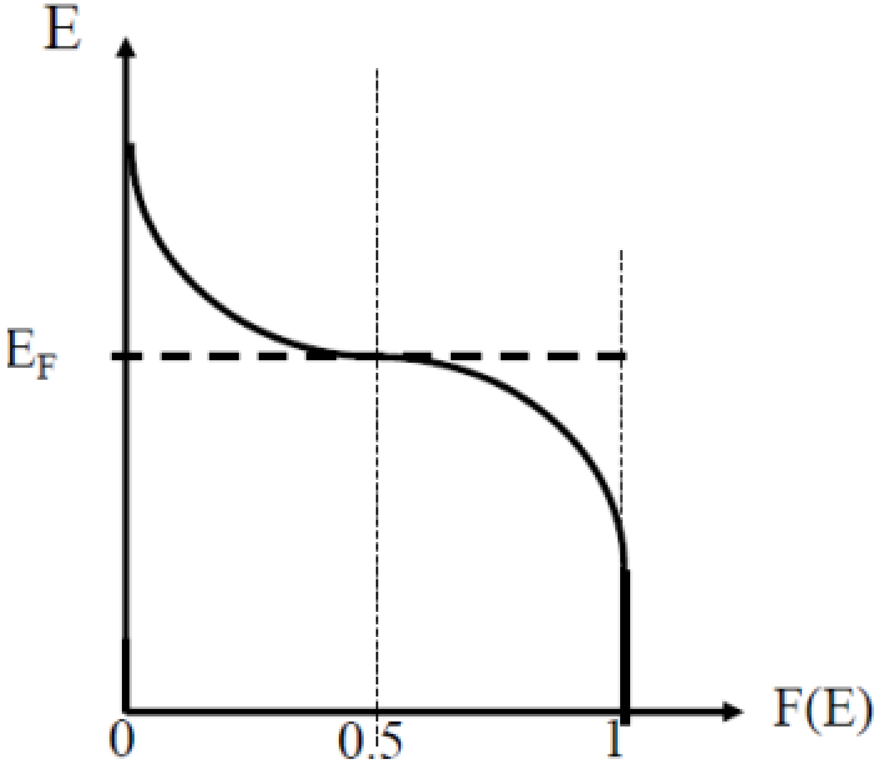
- The density of electrons in a semiconductor is related to the density of available states and the probability that each of these states is occupied.
- The density of occupied states per unit volume and energy is simply the product of the density of states and the Fermi-Dirac probability function (also called the Fermi function).
- Electrons in solids obey Fermi - Dirac distribution given by:

$$F(E) = \frac{1}{1 + e^{[(E - E_F)/kT]}}$$

- where k is Boltzmann's constant k =1.38x10^{-23} J/K,

  T is the temperature in kelvin.

- The function F(E) called the Fermi-Dirac distribution function which gives the probability that an electron occupies an electronic state with energy E.
- The quantity E_F is called the Fermi level, and it represents the energy level at which the probability to find an electron is 50%.



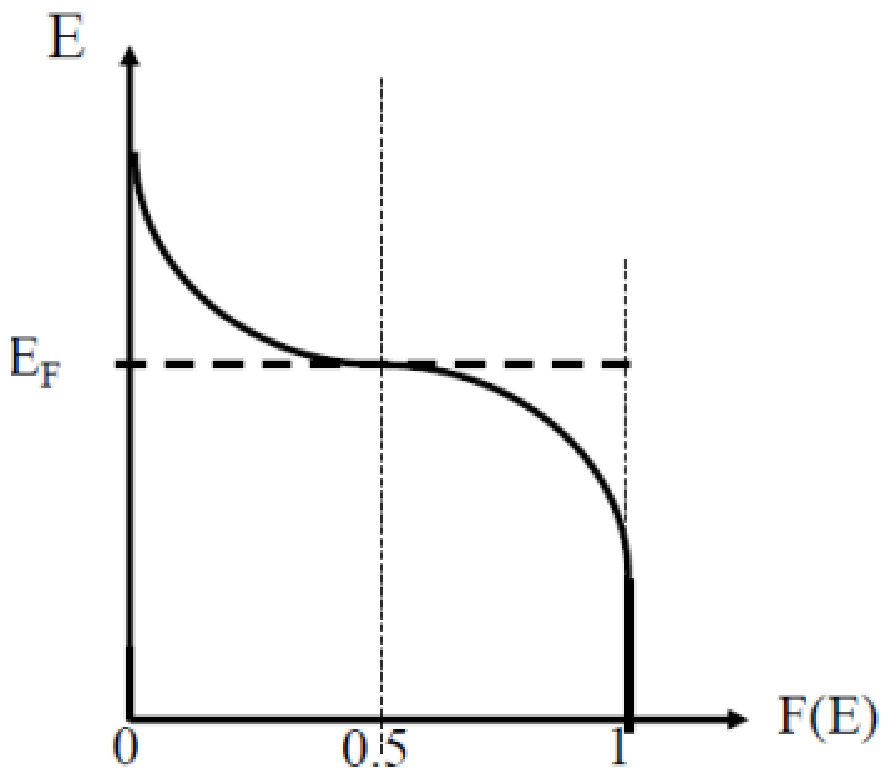
The Fermi – Dirac distribution function:

- The quantity E_F is called the Fermi level, and it represents the energy level at which the probability to find an electron is 50%.
- For an energy $E = E_F$ the occupation probability is:

$$F(E) = \frac{1}{1+e^{[(E-E_F)/kT]}}$$

$$F(E_F) = \left[1 + e^{[(E_F-E_F)/kT]}\right]^{-1} = \frac{1}{1+1} = \frac{1}{2}$$

This is the probability for electrons to occupy the Fermi level.



The Fermi – Dirac distribution function:

- At T=0 K, F(E) has rectangular shape:

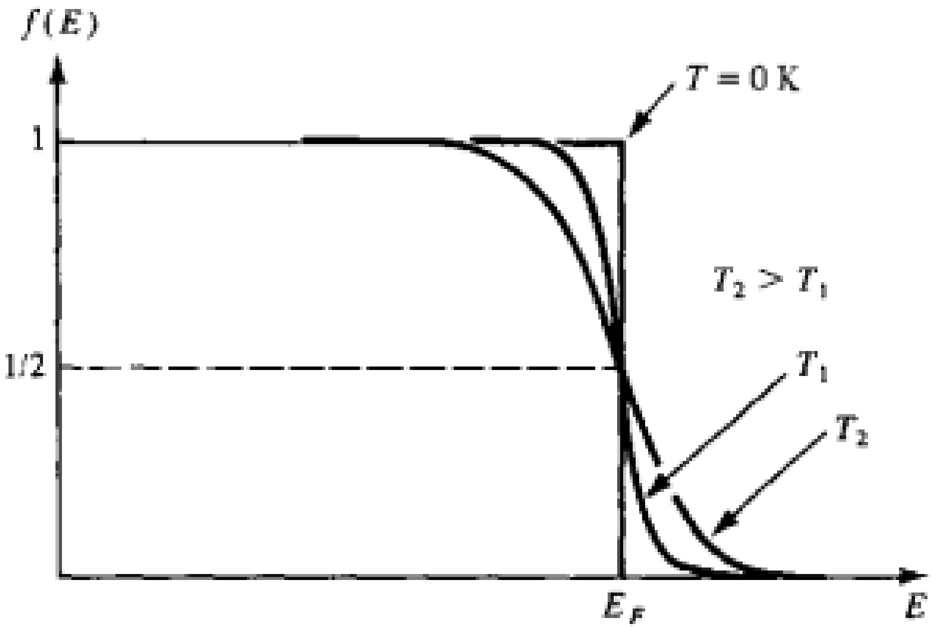
  the denominator of the exponent is

  1/(1+0) = 1 when (E<Ef), exp. negative

  1/(1+∞) = 0 when (E>Ef), exp. Positive

$$F(E) = \frac{1}{1 + e^{[(E-E_F)/kT]}}$$

- At 0 K every available energy state up to E_F is filled with electrons, and all states above E_F are empty.
- At temperatures higher than 0 K, some probability F(E) exists for states above the Fermi level to be filled with electrons and there is a corresponding probability [1 - F(E)] that states below E_F are empty.
- The Fermi function is symmetrical about E_F for all temperatures.



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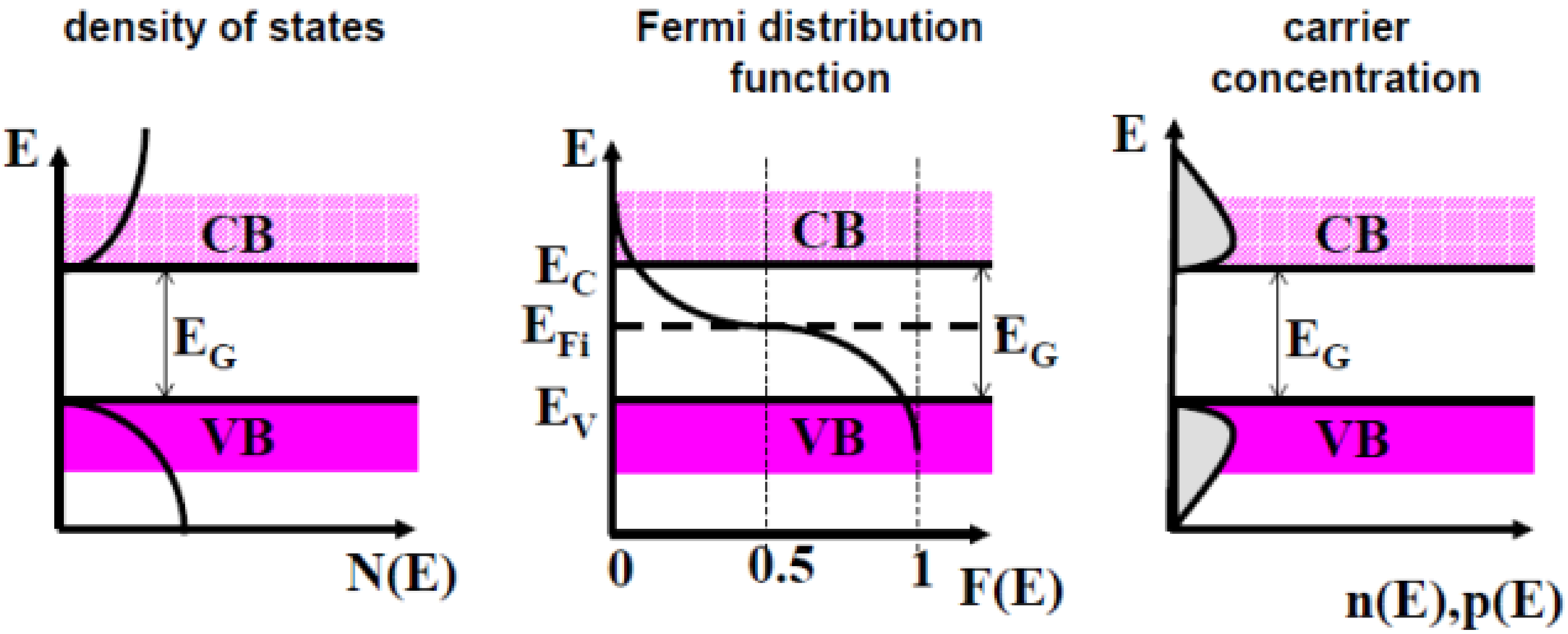
Carrier concentration in Intrinsic Semiconductor:



$$n = p = n_i = \int_{E_c}^{\infty} F(E)S(E)dE$$

- where S(E)dE is the density of states (cm-3) in the energy range dE. The subscript o used for the electron and hole concentration symbols (no, po) indicates equilibrium conditions.

Carrier concentration in Intrinsic Semiconductor:

$$n_o = \int_{E_c}^{\infty} F(E)S(E)dE$$

- electrons in conduction band

$$n_o = \int_{E_c}^{\infty} F(E)S_C(E)dE = N_C e^{-(E_C-E_F)/kT}$$

$$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$$

- holes in valence band

$$p_o = \int_{-\infty}^{E_v} [1-F(E)]S_v(E)dE = N_v e^{-(E_F-E_V)/kT}$$

$$N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$$

- N_c and N_v are the effective density of states in the conduction band and the valence band, respectively.
- where: h : Planc's constant h =6.6261x10^{-34} J s

  m_e : mass of electron

  m_h : mass of hole

Carrier concentration in Intrinsic Semiconductor:

- The product of n_o and p_o at equilibrium is a constant for a particular material and temperature (what is called the mass action law), even if the doping is varied:

$$n_o p_o = (N_c e^{[-(E_c - E_F)/kT]})(N_v e^{[-(E_F - E_v)/kT]})$$

$$= N_c N_v e^{[-(E_c - E_v)/kT]} = N_c N_v e^{[-E_g/kT]}$$

- For intrinsic semiconductors:

$$n_i p_i = (N_c e^{[-(E_c - E_{Fi})/kT]})(N_v e^{[-(E_{Fi} - E_v)/kT]})$$

$$n_i^2 = N_c N_v e^{[-E_g/kT]}$$

$$\therefore n_i = \sqrt{N_c N_v} e^{[-E_g/2kT]}$$

- The intrinsic electron and hole concentrations are equal (since the carriers are created in pairs), $n_i = p_i$; thus, the intrinsic concentration is

$$n_o p_o = n_i^2$$

- The intrinsic concentration for Si at room temperature is approximately $n_i = 1.5 \times 10^{10}$ cm^{-3}.

Carrier concentration in Intrinsic Semiconductor:

Fermi level in intrinsic semiconductor

From $n_i = N_C e^{-(E_C - E_{Fi})/kT}$ and $p_i = N_v e^{-(E_{Fi} - E_V)/kT}$

assuming: $n = p = n_i$

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln \frac{N_V}{N_C}$$

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{3}{4} kT \ln \frac{m_h}{m_e}$$

- Where E_F is called E_{Fi} (the intrinsic Fermi level)

Carrier concentration in Intrinsic Semiconductor:

Alternative expressions for n and p

Since:

$$n_i = N_C \exp\left(E_{Fi} - E_C / KT\right)$$

$$N_C = n_i \exp\left(E_C - E_{Fi} / KT\right)$$

Substitute in

$$n = N_C \exp\left(E_F - E_C / KT\right)$$

$$n = n_i \exp\left(E_C - E_{Fi} / KT\right) \exp\left(E_F - E_C / KT\right)$$

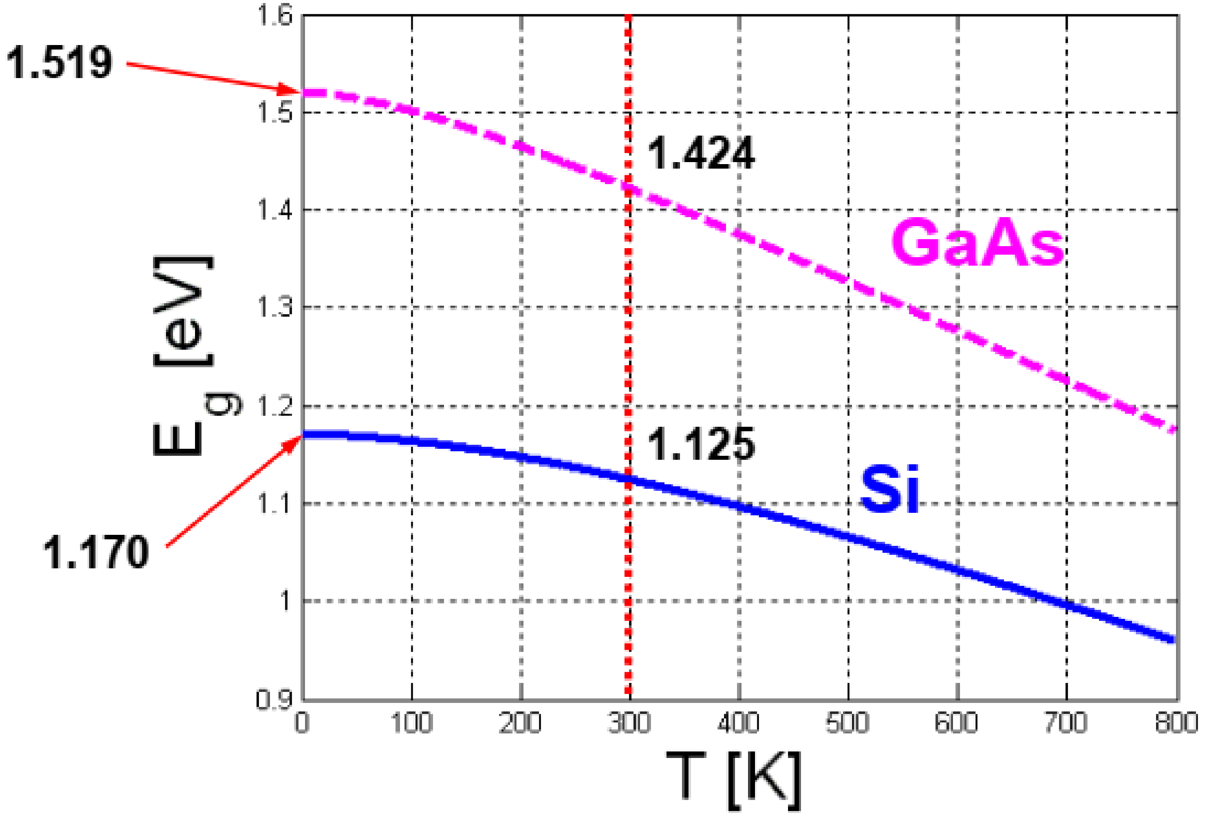
$$\boxed{n = n_i \exp\left(E_F - E_{Fi} / KT\right)}$$

Similarly, we can find p

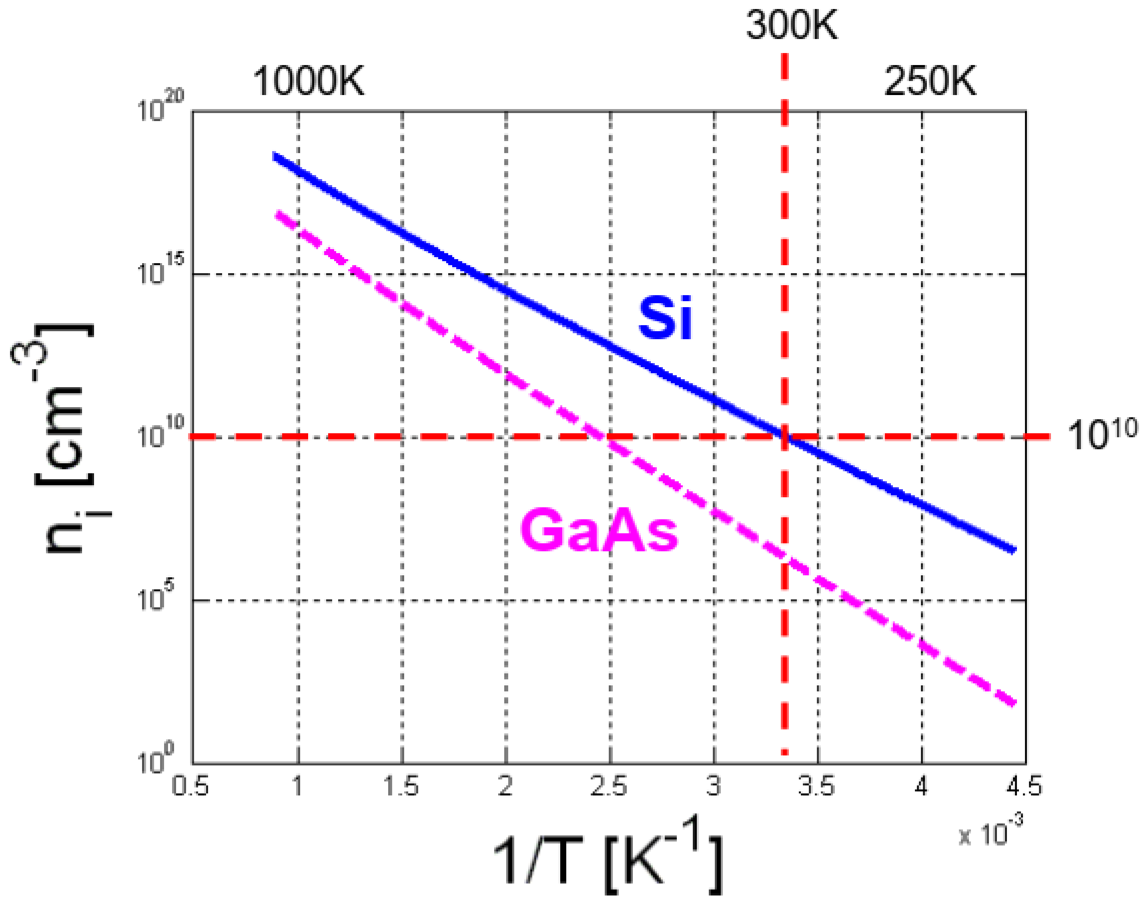
$$\boxed{p = n_i \exp\left(E_{Fi} - E_F / KT\right)}$$

Temperature effects:

❑ **Temperature effect on band gap**



❑ **Temperature effect on carrier concentration**



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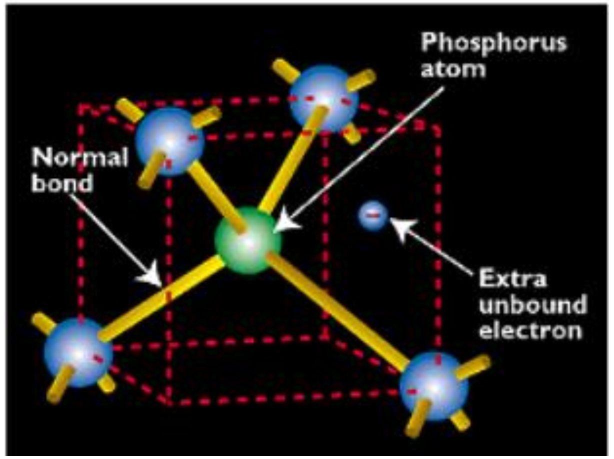
Extrinsic semiconductor:

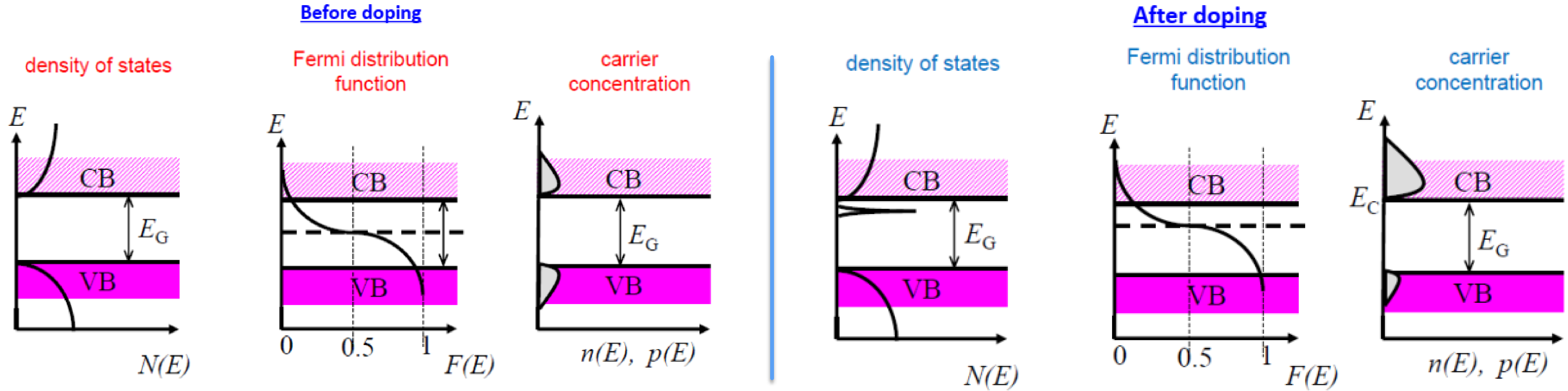
- An extrinsic semiconductor is one that has been doped, that is, into which a doping agent has been introduced, giving it different electrical properties than the intrinsic (pure) semiconductor.

	Intrinsic semiconductor	Donor atoms	Acceptor atoms
Group IV semiconductors	Silicon, Germanium	Phosphorus, Arsenic, Antimony	Boron, Aluminium, Gallium

n-type extrinsic semiconductors:

- Formed by adding donor atoms to the intrinsic semiconductor (Si)
- donors: pentavalent elements from group V (P, As, Sb) → release of electrons → n-type semiconductor





n-type extrinsic semiconductors:

Under complete ionization condition

$$n = N_D$$

Number of donor atoms

$$n = N_C e^{-(E_C - E_{Fn})/kT} = N_D$$

$$E_C - E_{Fn} = kT \ln(N_C / N_D)$$

$$\therefore E_{Fn} = E_C - kT \ln(N_C / N_D)$$

$$n = N_C e^{-(E_C - E_{Fn})/kT}$$

$$= N_C e^{-(E_C - E_{Fi} + E_{Fi} - E_{Fn})/kT}$$

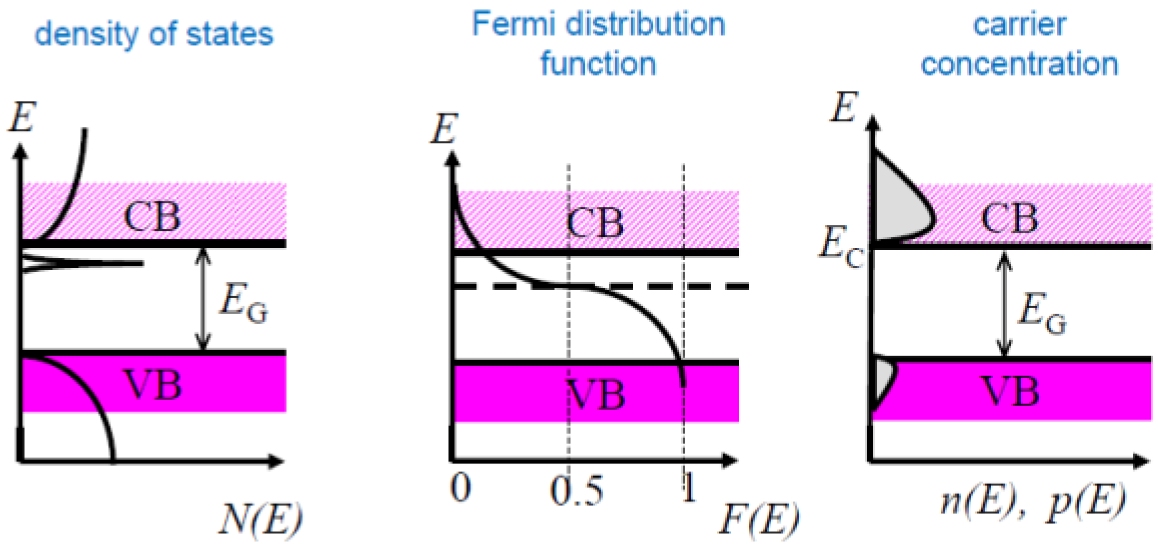
$$= \underbrace{N_C e^{-(E_C - E_{Fi})/kT}}_{n_i} e^{-(E_{Fi} - E_{Fn})/kT}$$

$$n = n_i e^{(E_{Fn} - E_{Fi})/kT}$$

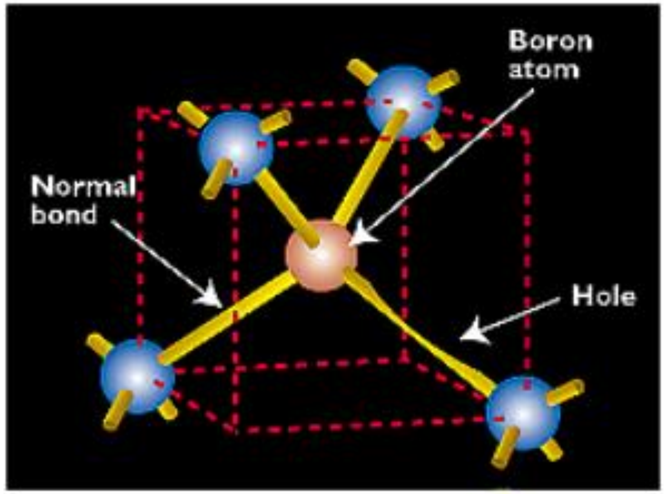
$$E_{Fn} = E_{Fi} + kT \ln \frac{n}{n_i}$$

Ascending Fermi level

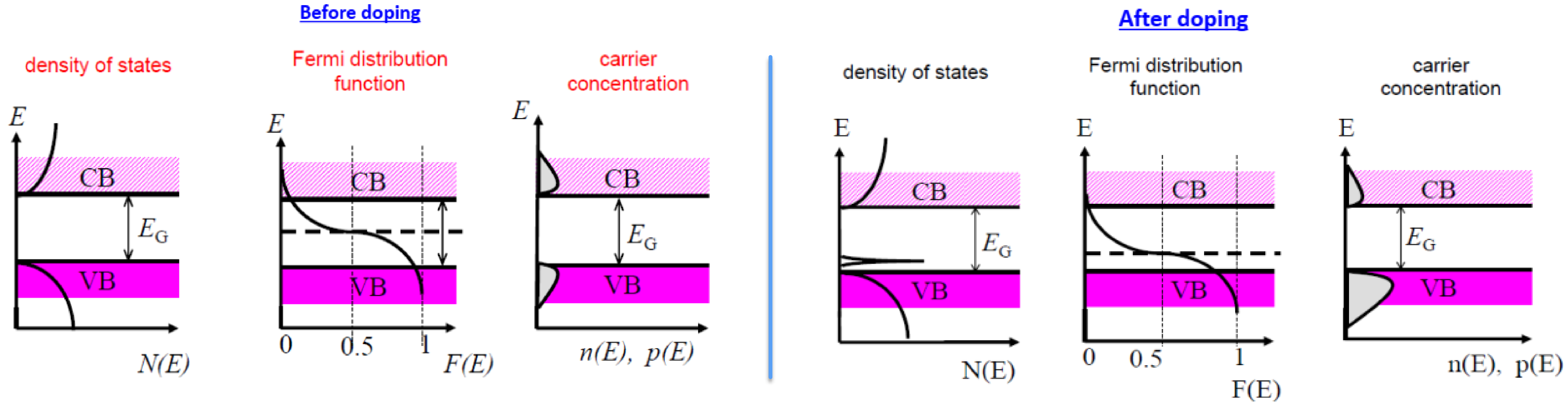
After doping



p-type extrinsic semiconductors:



- Formed by adding acceptor atoms to the intrinsic semiconductor (Si)
- Acceptors: trivalent elements from group III (B, Al, Ga) → capture of electron → hole remains → p-type semiconductor



p-type extrinsic semiconductors:

Under complete ionization condition

$$p = N_A$$

Number of acceptor atoms

$$p = N_V e^{-(E_{Fp} - E_V)/kT} = N_A$$

$$E_{Fp} - E_V = kT \ln(N_V / N_A)$$

$$\therefore E_{Fp} = E_V + kT \ln(N_V / N_A)$$

$$p = N_V e^{-(E_{Fp} - E_V)/kT}$$

$$= N_C e^{-(E_{Fp} - E_{Fi} + E_{Fi} - E_V)/kT}$$

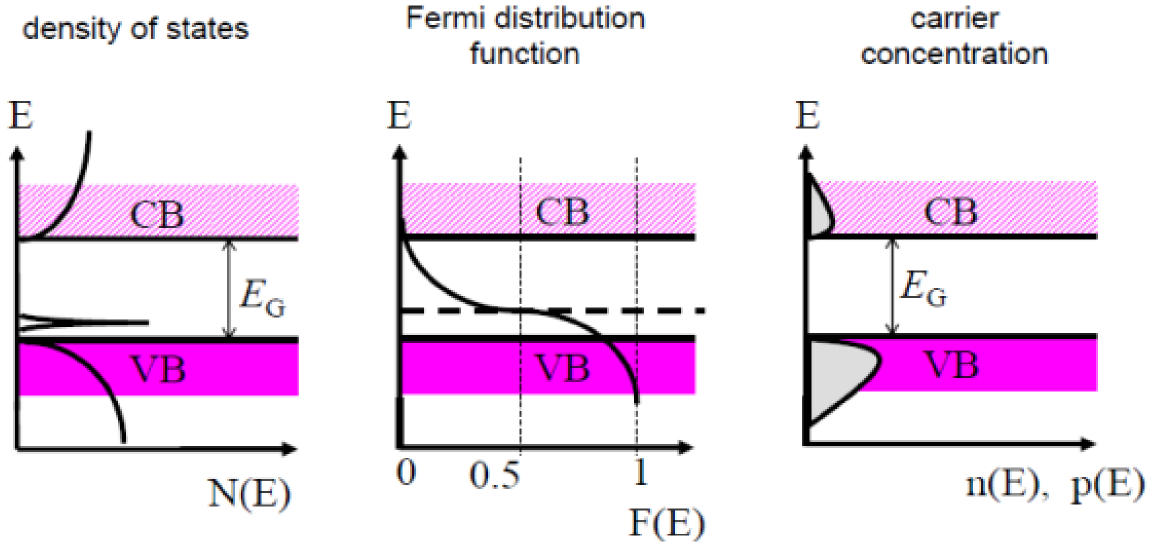
$$= \underbrace{N_C e^{-(E_{Fi} - E_V)/kT}}_{n_i} e^{-(E_{Fp} - E_{Fi})/kT}$$

$$p = n_i e^{(E_{Fp} - E_{Fi})/kT}$$

$$E_{Fp} = E_{Fi} - kT \ln \frac{p}{n_i}$$

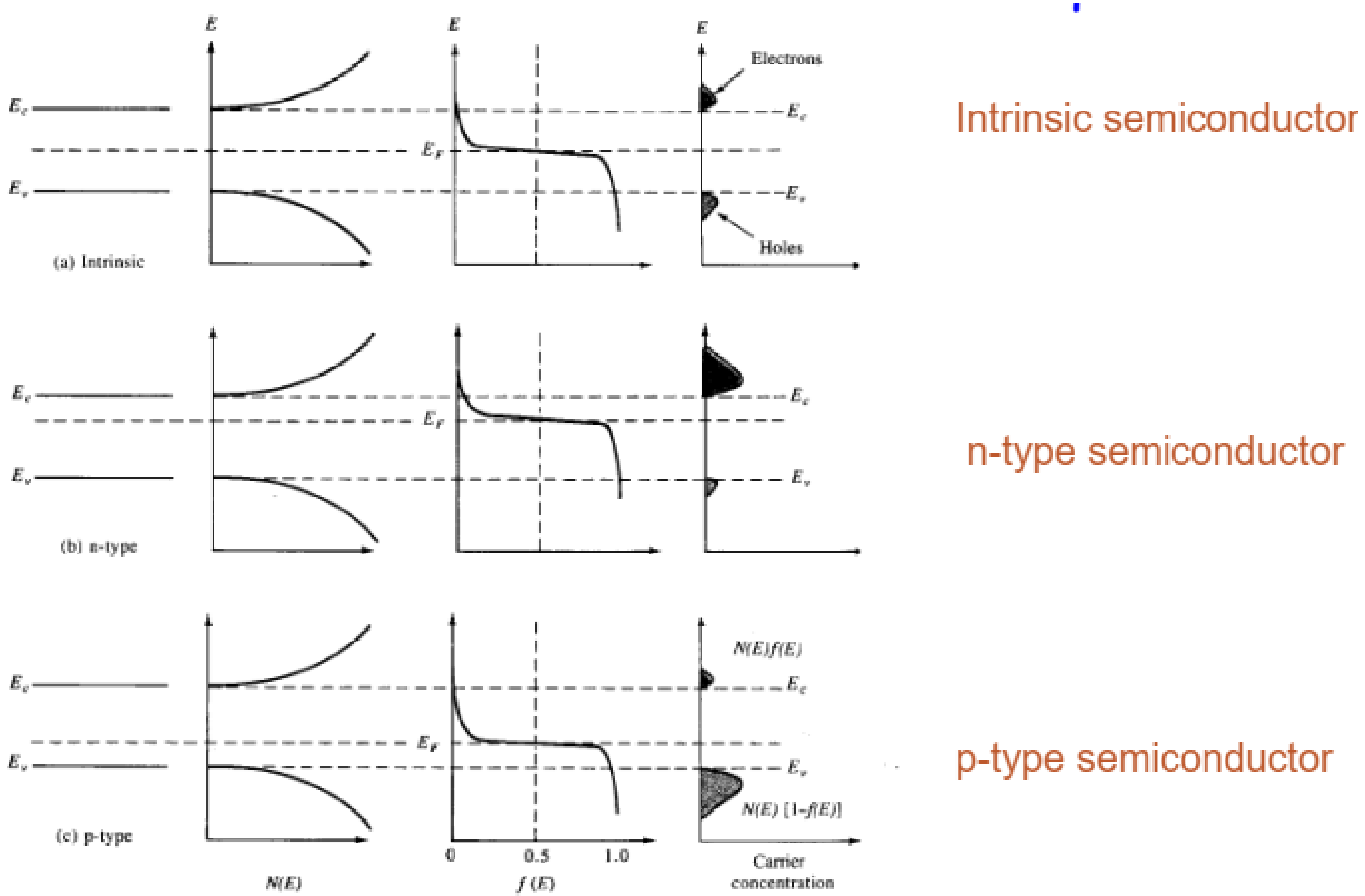
Descending Fermi level

After doping



Extrinsic semiconductor:

Band diagram, density of states, Fermi-Dirac distribution, and the carrier concentrations at thermal equilibrium



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Summary:

$$F(E) = \frac{1}{1+e^{[(E-E_F)/kT]}}$$

$$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$$

$$N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$$

$$n_i = N_C e^{-(E_C - E_{Fi})/kT}$$

$$n = n_i \exp\left(E_F - E_{Fi} / KT\right)$$

$$p_i = N_v e^{-(E_{Fi} - E_V)/kT}$$

$$p = n_i \exp\left(E_{Fi} - E_F / KT\right)$$

$$n_i = \sqrt{N_c N_v} e^{(-E_g/2kT)}$$

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln \frac{N_V}{N_C}$$

$$E_{Fn} = E_{Fi} + kT \ln \frac{n}{n_i}$$

$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{3}{4} kT \ln \frac{m_h}{m_e}$$

$$E_{Fp} = E_{Fi} - kT \ln \frac{p}{n_i}$$

h	=	6.6261×10^{-34} J s	Planck constant
m_e	=	9.1094×10^{-31} kg	free electron mass
e	=	1.6022×10^{-19} C	elementary charge
k	=	1.3807×10^{-23} J / K	Boltzmann constant

1 eV = 1.6022×10^{-19} C V = 1.6022×10^{-19} J

kT = 25.86 meV (at T = 300 K)

END OF LECTURE

BEST WISHES