Fundamentals of Engineering Physics I

Unit 8.- PHYSICAL PRINCIPLES OF SEMICONDUCTORS

1.- Para el modelo de los electrones libres en el comportamiento de los metales, se considera que los electrones son partículas totalmente libres dentro del conductor. En este modelo, debido al principio de exclusión de Pauli, la probabilidad de que un estado determinado con energía E esté ocupado por un electrón es igual a $f(E)$, la fracción de estados con esa energía, conocida como **factor de Fermi**, que están ocupados es (distribución de Fermi-Dirac):

The model of free electrons for the behaviour of metals considers that electrons are completely free particles inside the conductor. In this model, and due to the Pauli exclusion principle, the probability that a given state with energy E is occupied by an electron is equal to $f(E)$, which is the fraction of states with that energy and which is known as the **Fermi factor** (Fermi-Dirac distribution):

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

where E is energy, E_F is the Fermi energy or **Fermi level**, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann's constant and T is the absolute temperature. Calculate the value of the energies E for which the Fermi factor (the probability that a given state is occupied) is: (a) 1% and (b) 99%.

2.- In the free electron model, Fermi energy at absolute zero temperature is given by:

$$E_F = \frac{h^2}{8m_e}\left(\frac{3n}{\pi}\right)^{2/3}$$

where $h = 6.63 \times 10^{-34}$ J·s is Planck constant, $m_e = 9.11 \times 10^{-31}$ kg is the electron mass and n is the free electron concentration. Fermi energy shows the dividing line (in energy) between the states with the highest occupancy ($E < E_F$) and emptyness probability ($E > E_F$). Calculate the value of Fermi energy for copper at absolute zero temperature assuming that there is a free electron per each atom, that the copper density is 8.95×10^3 kg/m^3 and that its atomic mass is 63.5 g/mol.

3.-The concentration of free electrons in copper at low temperatures is $n = 8.45 \times 10^{28}$ m^{-3}. Using free-electron model, determine the Fermi energy for the solid copper and the value of the velocity of an electron whose kinetic energy equals the Fermi energy. Planck's constant, $h = 6.63 \times 10^{-34}$ J·s, electron mass, $m = 9.11 \times 10^{-31}$ kg.

4.- At absolute zero temperature, a semiconductor has a band structure, i.e., a forbidden E_G wide band gap separates the completely full valence band from the completely empty conduction band. However, at ordinary temperatures several electrons are excited and pass into the conduction band. Assuming that the Fermi energy of this semiconductor is half the band gap, calculate the value of the probability of occupying a specific state at the bottom of the conduction band for a temperature of 300 K if the width of the band gap is (a) 0.2 eV, (b) 1 eV, (c) 5 eV. Repeat the exercise for a temperature of 320 K.

5.- Determine, for an *n-type* semiconductor, the concentrations of electrons and holes depending on the donor impurity concentration N_D. Get the value of N_D so that the difference between the concentrations of electrons and donor impurities is less than 0.1% of N_D.

6.- It is known that for germanium, at a temperature of 300 K, intrinsic concentration is $n_i = 2.5 \times 10^{13}$ cm^{-3}. Determine, at that temperature, the concentrations of free electrons and holes, n and p, respectively, for a sample doped with germanium concentrations of acceptor and donor impurities $N_A = 10^{13}$ cm^{-3} and $N_D = 2 \times 10^{13}$ cm^{-3}, respectively.

7.- For a semiconductor, the intrinsic concentration n_i is a function of temperature. It is known that the experimental relationship that quantifies this dependence is:

$$n_i^2(T) = A_0 T^2 e^{-E_{G0}/kT}$$

where A_0 is a constant, T is the absolute temperature, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and E_{G0} is the forbidden band gap at absolute zero temperature.

Para el germanio la anchura de la banda prohibida en el cero absoluto es $E_{G0} = 0.78$ eV, mientras que la concentración intrínseca a 300 K vale $n_i = 2.5 \times 10^{13}$ cm^{-3}. Determinar: (a) El valor de la constante A_0 para el germanio. (b) La concentración intrínseca del germanio para una temperatura de 500 K. (c) Los valores de las concentraciones de electrones libres y huecos, n y p, respectivamente, para una muestra de germanio de tipo n dopada con una concentración de impurezas donadoras $N_D = 10^{15}$ cm^{-3}.

For germanium the width of the band gap at absolute zero is $E_{G0} = 0.78$ eV, while the intrinsic concentration at 300 K is $n_i = 2.5 \times 10^{13}$ cm^{-3}. Determine (a) The value of the constant A_0 for germanium; (b) The intrinsic concentration of germanium for a temperature of 500 K; (c) The values of the concentrations of free electrons and holes, n and p, respectively, for a sample of *n-type* germanium doped with a donor impurity concentration of $N_D = 10^{15}$ cm^{-3}.

8.- A sample of *n-type* silicon in thermal equilibrium at a temperature of 300 K has a resistivity $\rho = 500\ \Omega \cdot$m, electron and hole mobilities are $\mu_e = 0.16$ m^{2}V^{-1}s^{-1} and $\mu_p = 0.06$ m^{2}V^{-1}s^{-1}, respectively, the intrinsic carrier concentration is $n_i = 1.4 \times 10^{16}$ m^{-3} and the effective density of states in the conduction band (CB) is 10^{25} m^{-3}. If for the donor level $E_C - E_D = 0.05$ eV, where E is the minimum energy of the conduction band and E_D is the energy of donor level, determine (a) The concentrations of electrons and holes. (b) The energy of the Fermi level with respect to the energy of the CB. (c) The probability for a state of the donor level to be occupied and the probability to be not occupied.

9.- A *pn* junction diode has a saturation current of 0.5 mA at a temperature of 300 K. If we know that the value of the Boltzmann constant $k = 1.38 \times 10^{-23}$ J / K, determine the current at that temperature when the voltage has a value of 1, -1, 100 and -100 mV.

10.- A *pn* junction diode has a saturation current of 1 nA and $kT = 0.025$ eV at room temperature. (a) Find the value of the resistance for small reverse bias voltages. (b) Calculate the values of current and resistance of the diode in reverse bias when applying a voltage of 0.5 V. (c) Calculate the values of current and resistance of the diode in forward bias when applying a voltage of 0.5 V.

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