EE-545 Terms

Course Goal: The primary goal in this course could be summarized as (a) to understand semiconductor material properties, electrical conduction in semiconductors, p-n junction properties and (b) to develop the solid-state device characteristics (diode, transistor, FET, etc.) and study their applications in integrated circuits.

Therefore, it is highly recommended that as you study through these terms, you make up one or two examples for each to help you understand them better and thus enable you to achieve the above goal more effectively. For more clarity, you can also make up several sentences with each term as you proceed along.

NOTE: Any misunderstood word encountered in the following should definitely be looked up in an electronics or a regular dictionary. Failure to do so leads to more confusion. So, don't go any further in your studies, just do the right thing, look it up and clear up your confusion!

1. **Crystal:** A homogenous solid made up of an element or a chemical compound throughout which the atoms or molecules are arranged in a regularly repeating pattern (i.e. in a periodic fashion).

2. **Semiconductor:** A solid crystaline material (such as germanium or silicon) whose electrical conductivity is intermediate between that of a metal and an insulator, ranging from about 10^5 mhos/m to 10^{-7} mhos/m.

   Its conductivity is poor at low temperatures but is improved by minute additions of certain impurities (called dopants) or by the application of heat, light, or voltage (used in diodes, transistors, IC's, etc.).

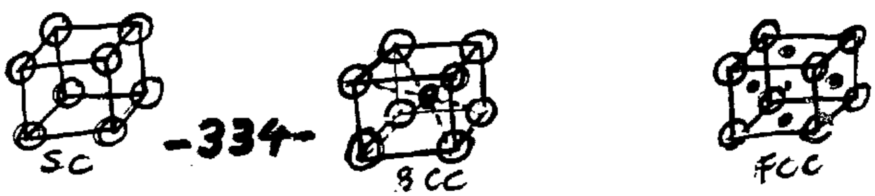
3. **Lattice:** A three-dimensional pattern of points in space, as of atoms or groups of atoms, in a crystal.

4. **Unit Cell (Also Called Structure Cell):** The smallest unit of structure of a crystal (in the form of a parallelapiped), whose exact repetition in three dimension along crystal axes generates the lattice of a given crystal.

5. **Basis Vector:** A set of three linearly independent vectors such that if the unit cell is translated by integral multiples of these vectors, a new unit cell identical to the original is found; $\vec{r} = \ell\vec{a} + m\vec{b} + n\vec{c}$ is the translation vector.

6. **Cubic Unit Cells:** Are the simplest three-dimensional lattices. There are three kinds of cubic unit cells. These are:

   6a. **Simple Cubic Unit Cell:** It has eight atoms located at each corner.
   6b. **Body Centered Cubic Unit Cell (BCC):** It is a simple cubic unit cell with an additional atom at the center of the cube.
   6c. **Face Centered Cubic Unit Cell (FCC):** It is a simple cubic unit cell with atoms centered on the six faces. These unit cells are shown below:



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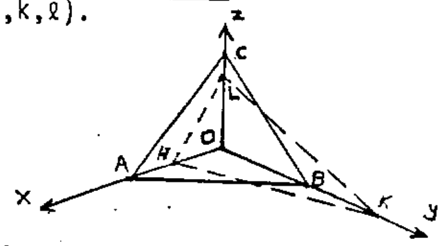
7. **Lattice Constant:** Is the distance between the nearest neighboring atoms on one of the sides of a cubic unit cell (i.e. one side of a cube).

8. **Miller Indices (or Crystal Indices):** Are three integers identifying a type of crystal plane. These three intergers are obtained by taking the reciprocal of the plane intercepts with the crystal axis and then reducing them to the smallest set of integers (h,k,ℓ).

ABC = unit plane

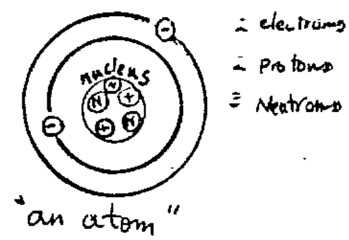
$(OA/OH,\ OB/OK,\ OC/OL) \longrightarrow (h, k, \ell)$



9. **Diamond Lattice:** Can be considered to be an FCC structure with an extra atom placed at $\bar{r}_d = \bar{a}/4 + \bar{b}/4 + \bar{c}/4$ from each of the FCC atoms. In other words, the original FCC has associated with it a second interpenetrating FCC displaced by (1/4, 1/4, 1/4).

10. **Electron (also called negatron):** An elementary particle which is constituent of ordinary matter. It carries one unit of negative electricity (-1.6×10^{-19} coulomb) and has a very small mass (9.1×10^{-28} g) Electrons surround the positively charged nucleus and determine the chemical properties of the atom.

11. **Atom:** The smallest particle of a chemical element that can take part in a chemical reaction without being permanently changed. An atom is made up of protons and neutrons in a central nucleus surrounded by electrons. In all atoms, the number of electrons equal the number of protons.



12. **Spectrum:** The set of frequencies (or wavelengths) involved in some process. For example, each element has a characteristic discrete spectrum for emission and absorption of light.

13. **Bohr Theory:** A theory of atomic structure postulating an electron moving in one of a certain discrete circular orbits about a nucleus. Through absorption or emission of a photon of energy, the electrons may shift to an orbit of higher or lower energy.

14. **Quantum Mechanics (also called quantum theory):** Is the theory that states whenever radiant energy is transferred, the transfer occurs in pulsations rather than continuously and that the amount transferred during each pulsation is only in multiples of definite, indivisible units called quanta (which is the plural of quantum).

15. **Quantum:** Is the unit carrier of energy, e.g. the photon for light (or electromagnetic radiation) and the electron for electricity.

16. **Heisenberg Uncertainty Principle:** Is the precept that the accurate measurement of an observable quantity necessarily produces uncertainties in one's knowledge of the values of other observables.

17. **Wave Function (in a wave equation):** Is a point function that specifies the amplitude of a wave. (ψ) b) Solution of the Schrödinger's Wave Equation.

18. **The Schrödinger Wave Equation:** Is a partial differential equation governing the wave function ψ of a system of one or more non-relativistic particles (particles whose velocities are small compared to that of light).

19. **Tunnel Effect (also called tunneling):** (a) Is the probability that a particle of given potential energy can penetrate a finite barrier of higher potential. (b) Piercing of a rectangular potential barrier in a semiconductor by a particle that does not have sufficient energy to go over the barrier.

20. **Pauli Exclusion Principle:** Is the principle which states that if particles are considered to occupy quantum states, then only one particle of a given kind can occupy any one state. (Note that particles differ in kind due to their direction of spin, momentum, orbit, etc.)

21. **Bonding:** Is the joining together of atoms to form molecules or crystalline salts.

22. **Bond (also called chemical bond):** The strong attractive force that holds together atoms in molecules and in crystalline salts. There are three kinds of bonds between atoms as follows:

22a. **Ionic Bond:** A type of chemical bonding in which one or more electrons are transferred completely from one atom to another, thus converting the neutral atoms into electrically charged ions; these ions are approximately spherical and attract one another because of their opposite charge (e.g. NaCl).

22b. **Metallic Bond:** The type of chemical bond that is present in all metals and may be thought of as resulting from a sea of valence eletrons which are free to move throughout metal lattice (Lattice is made of immobile ions) - (e.g. Na).

22c. **Covalent Bond (also called electron-pair bond):** Is a bond in which each atom of a bound pair contributes one electron to a shared pair that constitutes an ordinary chemical bond (e.g. Ge, Si, C, etc.).

23. **Energy Bands:** As many atoms are brought together in a solid, the split energy levels from each atom form bands of energies in which the energies of electrons lie or from which electrons are excluded. Different bands of energies are described below.

23a. **Conduction Band:** Is the upper energy band in which electrons can move freely in a solid, producing net transport of charge.

23b. **Valence Band:** Is the lower energy band which can be filled with electrons and in which vacancies can move about.

23c. **Energy Gap (also called forbidden gap or band gap):** The energy range between the bottom of the conduction band and the top of the valence band of a semiconductor. In a perfect semiconductor, the energy gap contains no electron energy states, thus the name forbidden gap.

24a. Metal: A material that has high electrical and thermal conductivity at normal temperatures. The band structure is shown below.

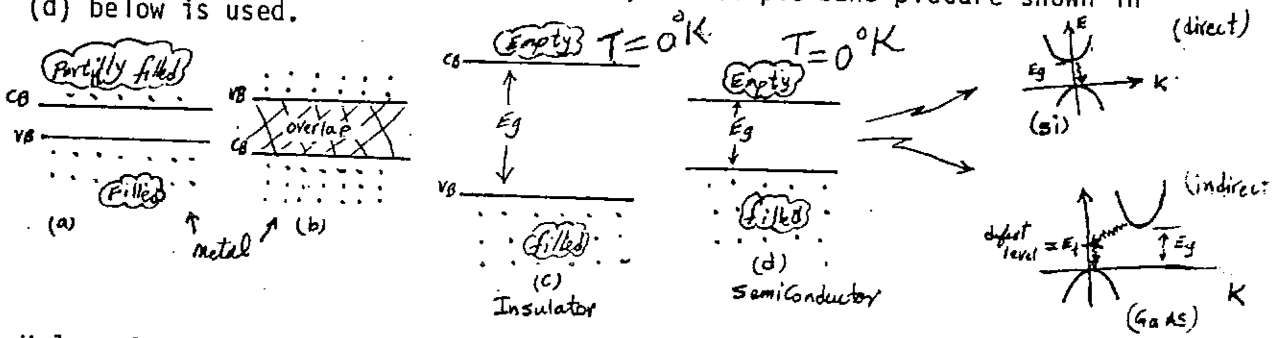
24b. Insulator: A material in which the outer electrons are tightly bound to the atom and are not free to move. Thus, conductivity is very poor. See its energy band structure below.

24c. Semiconductor: Is already defined in #2 and its band structure is shown below. There are two classes of semiconductor energy bands: direct and indirect.

a. Direct Semiconductor: Is such that an electron in the conduction band can fall to an empty state in the valence band, giving off the energy difference E_g as a photon of light.

b. Indirect Semiconductor: In this kind of semiconductor, an electron in the conduction-band minimum cannot fall directly to the valence-band maximum but must undergo a momentum change as well as changing its energy.

Note: For both kinds of semiconductors, the simple band picture shown in (d) below is used.



25. Hole: A vacant electron energy state near the top of the valence band in a semiconductor. It behaves as though it were a positively charged particle.

26. Electron-Hole Pair (EHP): Comes about when a conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band.

27. Effective Mass: Are two parameters with the dimensions of mass that are assigned to electrons and holes in a solid. Therefore, most of the influences of the lattice on the electrons and holes are accounted for in this manner. In the presence of an external electromagnetic field or any calculation involving the mass of the charge carriers, the electrons and holes behave in many respects as if they were free but with a mass equal to these parameters rather than their true masses.

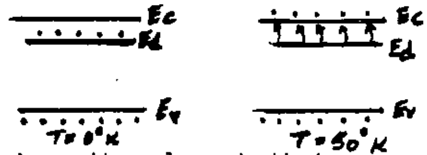
28. Intrinsic Semiconductor: Is a perfect semiconductor crystal with no impurities or lattice defects. In this semiconductor the concentration of charge carriers is characteristic of the material itself rather than the content of impurities and structural defects of the crystal. For $T > 0°K$, EHP's are generated as valence band electrons are excited thermally across the energy gap (E_g) to the conduction band ($n_o = p_o = n_i$).

28a) Doping: The adding of controlled amounts of impurities (or dopants) to a semiconductor crystal in order to control its properties.

29. Extrinsic Semiconductor: A semiconductor whose electrical properties are dependent on impurities added to the semiconductor crystal (called doping). 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 e^-) and p-type (mostly h^+) and the equilibrium carrier concentrations n_0 and p_0 are different from the equilibrium carrier concentration n_i.

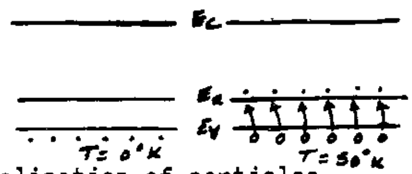
30. Donor (also called electron donor): Is an impurity that is added to a pure semiconductor material to increase the number of free electrons (all atoms from column V such as P, Sb, As, etc.).

31. Donor Level: Is an intermediate energy level close to the conduction band in the energy diagram of an extrinsic semiconductor. (n_0 at $50°K \gg P_0$)



32. Acceptor (also called electron acceptor): Is an impurity element that increases the number of holes in a semiconductor crystal. Examples are: Al, In, Ga, and B (all atoms from Column III).

33. Acceptor Level: Is an intermediate energy level in the band gap close to the top of the valence band in the energy diagram of an extrinsic semiconductor. (P_0 at $T=50°K$) $\gg$ (n_i, n_0)



→ 34. Recombination: The combination and resultant neutralization of particles or objects having unlike charges, such as a hole and an electron (or in other words, the simultaneous elimination of both an electron and a hole in a semiconductor).

35. Fermi-Dirac Distribution Function: A function specifying the probability that an electron in a semiconductor will occupy a certain available energy state when thermal equilibrium exists. The function is given by:

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

Nearly all energy levels below the fermi level (E_F) are filled and nearly all above E_F are empty.

36. Density of States [N(E)]: Is a function of energy E equal to the number of quantum states (in the energy range E and E + dE) divided by the product of dE and the volume of the substance. i.e. $N(E) = dN/dE$ where N = total number of states/unit volume.

37. Effective Density of States N_C (or N_V): Is a representation of all of the distributed electron states in the conduction (or valence) band and located at the edge of the conduction (or valence) band.

$n_0 = \int_{E_c}^{\infty} f(E) N(E)\, dE \approx N_c f(E_c)$

38. Carrier (also called charge carrier): Is a mobile hole or a mobile conduction electron in a semiconductor.

39. Mobility (also called drift mobility): Is defined to be the average drift velocity of carriers (electrons or holes) per unit electric field in a homogeneous semiconductor. It shows the ease with which carriers move through a semiconductor when subjected to electric forces. In general, holes and electrons do not have the same mobility and change for different semiconductors. For example, the carrier mobility in Ge is higher than in Si.

40. Electrical Conductivity: The ratio of the electric current density (j) to the electric field (E) in a material. It represents the ability to conduct or transmit electricity. $\sigma = J/E$

41. Diffusion(←caused by carrier gradient): Is the movement of carriers from a region of high concentration to regions of lower concentration.

42. Drift(←caused by an electric field): The movement of carriers in a semiconductor under the influence of an applied voltage.

43. Continuity Equation: An equation obeyed by any conserved, indestructable quantity such as electric charge, thermal energy, electrical energy, etc. which is essentially a statement that the rate of increase of the quantity in any region equals the total current flowing into the region.

44. p-n Junction: The region of transition between p-type and n-type material in a single semiconductor crystal. It contains a permanent dipole charge layer.

45. There are several methods of forming a p-n junction as follows:

45a. Grown Junction Technique:
A junction produced by changing the types and amounts of donor and acceptor impurities that are added during the growth of a semiconductor crystal from a melt.

45b. Alloyed Junction (or fused junction) technique: Is a method of producing a junction by alloying one or more impurity metals to a semiconductor. (Alloying forms a P or n region depending on the impurity used.)

45c. Diffused Junction Technique (most common technique): A technique in which the p-n junction is formed by the diffusion of an impurity within a semiconductor crystal.

45d. Ion-Implantation Technique: A method of semiconductor doping (and thus forming a p-n junction) by introducing impurities that have been ionized and accelerated to high velocity. This directed beam of ions would penetrate and become deposited in the near-surface regions.

46. Types of Junctions: There are two types of junctions: (a) step junction, which has uniform p-doping on one side of a sharp junction and uniform n-doping on the other side; (b) graded junction, in which (Na-Nd) varies over a significant distance on either side of the junction.

47. Equilibrium: A condition in which no change occurs in the state of a system as long as its surroundings are unaltered.

48. Contact Potential: Is the equilibrium potential difference between the p and the n materials on either side of a junction. Due to equilibrium, no net current can result from this potential difference.

49. Transition Region (also called depletion layer, space charge layer): Is the charged region at either side of the junction in which donor and acceptor ions are positioned.

50. **Forward Bias:** An external voltage applied in the conducting direction of a pn junction. The positive terminal is connected to the p-type region and the negative terminal to the n-type region.

51. **Reverse Bias:** An external voltage applied to a pn junction to reduce the current flow across the junction and thereby widen the depletion region. It is the opposite of forward bias.

52. **Carrier Injection:** Is the increase in charge of minority carrier concentration due to a forward bias.

53. **Carrier Extraction:** Is the decrease in charge of minority carrier concentration due to a reverse bias.

54. **Breakdown:** A large usually abrupt rise in electric current in the presence of a small increase in voltage; can occur in a confined gap between two electrodes, the atmosphere (as lightning) and a reverse-biased semiconductor pn junction.

55. **Zener Breakdown (also called zener effect):** A nondestructive breakdown in a pn junction due to the presence of a high electric field at the junction. This field is high enough to produce a form of field emission that suddenly increases the number of carriers at the junction.

56. **Avalanche Breakdown:** A nondestructive breakdown caused by the cumulative multiplication of carriers through field-induced impact ionization.

57. **Schottky Barrier:** A simple metal-to-semiconductor interface that serves as a rectifying barrier at the junction.

57a. **Schottky Barrier Diode (also called Schottky Diode, hot-carrier diode):** A semiconductor diode formed by contact between a semiconductor layer and a metal coating; it has a nonlinear rectifying characteristic; hot carriers (electrons for n-type material or holes for p-type material) are emitted from the Scottky barrier of the semiconductor and moved to the metal coating that is the diode base. Since the majority carriers predominate, there is essentially no injection or storage of minority carriers to limit switching speeds.

58. **Ohmic Contact:** A region where two materials are in contact, which has the property that the current flowing through it is proportional to the potential difference acting on it (i.e. the region obeys the ohm's law $V = RI$).

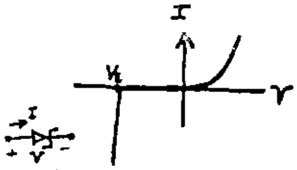
59. **Ideal Diode:** Is a nonlinear two terminal device which acts as a short circuit when forward biased and as an open circuit when reverse biased.

60. **Junction Diode:** A two terminal device which will conduct electrically more easily in one direction than in the other.

61. **Rectifier:** A device which by virtue of its asymmetrical conduction characteristic, converts an alternating current into a unidirectional current.

62. **Punch-Through (also called reach-through):** For a reverse-biased junction, it is the condition where the transition region (w) extends primarily into the lightly doped region until it fills the entire length and makes electrical contact with another junction.

63. **Zener Diode:** A semiconductor diode that above a certain reverse voltage (V_Z) has a sudden rise in current. In forward bias it acts as an ordinary diode.



64. **Voltage Regulator:** A device that maintains or varies the terminal voltage of a generator or other machines at a predetermined value.

65. **Varactor Diode (also called voltage controlled capacitor):** A pn junction semiconductor diode designed for low losses at high frequencies. Its capacitance varies with the applied reverse voltage. In the normal diode, efforts are made to minimize inherent capacitance, while in the varactor, this capacitance is emphasized.

66. **Degenerate Semiconductor:** A heavily doped semiconductor.

67. **Photo Diode:** A semiconductor diode in which the reverse current increases whenever light falls on the diode junction.

68. **Light Emitting Diode (LED):** A pn junction that emits light when forward biased.

69. **Bipolar Junction Transistor (BJT):** Is a nonlinear three terminal (E,B,C), solid state device that can control the flow of current and thus is capable of signal amplification and switching. It consists of three semiconductor regions and two pn junctions.

70. **Amplification:** Increase in the magnitude or power level of a time-varying physical quantity (such as AC-voltage), without distorting the wave shape of the quantity.

71. **Switching:** Making, breaking, or changing the connections in an electric circuit.

72. **Cut-Off:** The condition when the emitter-base junction of a transistor has zero bias or is reverse biased and there is no collector current ($I_C = 0$).

73. **Saturation:** The operating condition of a transistor when an increase in base current produces no further increase in collector current ($V_{CE} \simeq 0.3$).

74. **Load Line:** A line drawn on the collector characteristic curves of a transistor on which the operating point of the transistor moves as the collector current (i_C) changes.

75. **Transit Time:** The average time a minority carrier takes to diffuse from emitter to collector in a junction transistor.

76. **Integrated Circuits (IC):** A combination of interconnected circuit elements inseparably associated on or within a continuous substrate.

77. **Categories of IC's:** The most common categories are "linear" or "digital" according to application and "monolithic" or "hybrid" according to fabrication. These are described below:

78a. **Linear IC (also called analog IC):** Is an IC which performs amplification or other linear operations on signals. e.g. amplifiers, op amps, and analog communication circuits.

78b. **Digital IC:** Is an IC in which the output varies in discrete steps or pulses. This kind of IC involves logic and memory circuits for use in computers, calculators, microprocessors, etc.

79a. **Monolithic Circuit:** Are integrated circuits entirely on a single chip of semiconductor.

79b. **Hybrid Circuit:** Are integrated circuits which contain one or more monolithic circuits or individual transistors bonded to an insulating substrate and properly interconnected to passive elements (such as capacitors, resistors, etc.).

80. **Fabrication Process:** The basic processing steps that are used to fabricate various silicon devices such as diodes, transistors and IC's can be summarized as follows:

    1. Diffusion (and ion implantation)
    2. Oxidation
    3. Photolithography
    4. Chemical-vapor deposition (including epitaxy)
    5. Metallization

    Starting with single-crystal silicon wafers, the process listed above can be used to produce functioning discrete devices (i.e. individual diodes and transistors) and IC's. These devices or IC's will be in wafer form, with hundreds or thousands of devices or IC's on the same silicon wafer. The wafer must be then divided up to obtain the individual dice or chips. The chips are then encapsulated or packaged.

81. **Photolithography:** Is a method of producing microscopically small circuits and device patterns on silicon wafers, resulting in as many as 10,000 transistors on a 1 cm x 1 cm chip. Using ultraviolet light exposure, device dimensions or line widths as small as 2 μm can conventionally be obtained. Using electron-beam or x-ray exposure, device dimensions as small as 0.2 μm (submicron) can be achieved.

82. **MOS Device (metal-oxide semiconductor):** (a) A field effect transistor in which the gate electrode is isolated from the channel by an oxide film, (b) A capacitor in which semiconductor material forms one plate, aluminum forms the other plate, and an oxide forms the dielectric.

83. **Charge Transfer Devices:** Are dynamic devices which move charge under the control of clock pulses. These devices have applications in memories, logic functions, signal processing, etc. e.g. charge coupled device (CCD) which works on the basis of dynamic storage and withdrawal of charge in a series of MOS capacitors.

84. **Large Scale Integration (LSI):** An integrated circuit with a typical complexity of hundreds to thousands of logic gates and transistors on a single chip. Note that, the number of gates per chip used to define LSI depends on the manufacturer.