

ESE 2017
UPSC ENGINEERING SERVICES EXAMINATION

Preliminary Examination

**Paper
I**

**General Studies and
Engineering Aptitude**

8

**Basics of Material Science
and Engineering**

Comprehensive Theory *with* Practice Questions

As per new syllabus of ESE 2017



www.madeasypublications.org



MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016

E-mail: infomep@madeeasy.in

Contact: 011-45124660, 08860378007

Visit us at: www.madeeasypublications.org

ESE-2017 : Preliminary Examination
Paper-I : General Studies and Engineering Aptitude

Basics of Material Science and Engineering

© Copyright, by MADE EASY Publications.

All rights are reserved. No part of this publication may be reproduced, stored in or introduced into a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photo-copying, recording or otherwise), without the prior written permission of the above mentioned publisher of this book.

1st Edition : 2016

MADE EASY PUBLICATIONS has taken due care in collecting the data and providing the solutions, before publishing this book. In spite of this, if any inaccuracy or printing error occurs then MADE EASY PUBLICATIONS owes no responsibility. MADE EASY PUBLICATIONS will be grateful if you could point out any such error. Your suggestions will be appreciated.

© All rights reserved by MADE EASY PUBLICATIONS. No part of this book may be reproduced or utilized in any form without the written permission from the publisher.

Preface

The compilation of this book **Basics of Material Science and Engineering** was motivated by the desire to provide a concise book which can benefit students to understand the concepts of energy and environment topics.

This textbook **Basics of Material Science and Engineering** provides all the requirements of the students, i.e. comprehensive coverage of theory, fundamental concepts and objective type questions articulated in a lucid language. The concise presentation will help the readers grasp the theory of this subject with clarity and apply them with ease to solve objective questions quickly. This book not only covers the syllabus of ESE but also addresses the need of many other competitive examinations. Topics like 'Introduction, Chemical Bonding, Crystallography, Electronic Materials, Magnetic Properties of Materials, Ceramics, Polymers, Composites, Mechanical Properties of Materials, Ferrous Metals, Non-Ferrous Metals and Alloys' are given full emphasis, keeping in mind of our research on their importance in competitive examinations.

We have put in our sincere efforts to present detailed theory and MCQs without compromising the accuracy of answers. For the interest of the readers, some notes, do you know and interesting facts are given in the comprehensive manner. At the end of each chapter, sets of practice question are given with their keys, that will allow the readers to evaluate their understanding of the topics and sharper their question solving skills.

Our team has made their best efforts to remove all possible errors of any kind. Nonetheless, we would highly appreciate and acknowledge if you find and share with us any printing and conceptual errors.

It is impossible to thank all the individuals who helped us, but we would like to sincerely thank all the authors, editors and reviewers for putting in their efforts to publish this book.



B. Singh (Ex. IES)

With Best Wishes

B. Singh

CMD, MADE EASY

Basic of Material Science & Engineering

Chapter 1

Introduction 1

- 1.1 Historical Perspective1
- 1.2 Material Science1
- 1.3 Classification of Materials.....1
 - 1.3.1 Advanced Materials2
 - 1.3.2 Semiconductors.....2
 - 1.3.3 Smart Materials2

Chapter 2

Chemical Bonding 3

- 2.1 Fundamental Concepts..... 3
- 2.2 Electrons in Atoms..... 4
- 2.3 The Periodic Table..... 4
- 2.4 Chemical Bonding 5
- 2.5 Ionic Bond..... 5
- 2.6 Covalent Bond..... 6
- 2.7 Metallic Bond..... 7
- 2.8 Comparison of Primary Bonds 8
- 2.9 Dispersion Bonds 8
- 2.10 Dipole Bonds 8
- 2.11 Hydrogen Bonds 9
- Objective Brain Teasers* 10

Chapter 3

Crystallography 12

- 3.1 Introduction 12
- 3.2 Comparison of Crystalline and Noncrystalline Solids 12
- 3.3 Lattice Points, Space Lattice and Crystal Structures 13
- 3.4 Unit Cell and Primitive Unit Cell..... 14
- 3.5 Bravais Lattices..... 14
- 3.6 Cubic Crystal Structures 16

- 3.6.1 Simple Cubic Crystal Structure (SCC) 16
- 3.6.2 Body Centred Cubic Structure (BCC) 17
- 3.6.3 Face Centered Cubic Structure (FCC) 17
- 3.6.4 Diamond Cubic (DC) Structure 18
- 3.7 Hexagonal Closed Packing 19
- 3.8 Miller Indices..... 20
 - 3.8.1 Determining the Miller Indices of a Given Plane..... 20
- 3.9 Planar Density 21
- 3.10 Interplanar Spacing 21
- 3.11 Crystal Imperfections 22
 - 3.11.1 Types of Imperfections Present in Solids .. 22
- 3.12 Point Imperfections..... 22
 - 3.12.1 Vacancies 23
 - 3.12.2 Interstitial Defect 23
 - 3.12.3 Substitutional Imperfections 24
 - 3.12.4 Frenkel's Defect 24
 - 3.12.5 Schottky's Defect 24
- Objective Brain Teasers* 25

Chapter 4

Electronic Materials..... 27

- 4.1 Introduction..... 27
- 4.2 Ohm's Law and Electrical Conductivity..... 28
- 4.3 Energy Band Structure in Solids 30
- 4.4 Classification of Materials based upon Energy Band Diagram 32
 - 4.4.1 Insulators 32
 - 4.4.2 Semiconductors 32
 - 4.4.3 Metals 32
- 4.5 Electrical Resistivity of Metals..... 33
- 4.6 Thermal Conductivity of Metals–Wiedemann Franz law 34
- 4.7 Thermoelectric Phenomenon 35

4.8 Superconductivity	35
4.8.1 Meissner Effect	36
4.8.2 Effect of Magnetic Field (H).....	36
4.8.3 Silsbee's Rule	37
4.8.4 Other Properties of Superconductivity	37
4.8.5 Types of Superconductors.....	37
4.8.6 Applications of Superconductor	38
4.9 Insulators.....	38
4.10 Dielectrics	39
4.10.1 Dielectric Constant.....	40
4.10.2 Dielectric Strength	41
4.11 Electric Dipole Moment and Polarization	41
4.12 Types of Polarization.....	43
4.12.1 Electronic Polarization	43
4.12.2 Ionic Polarization	44
4.12.3 Orientation Polarization	44
4.12.4 Space Charge Polarization.....	44
4.13 Phase Difference and Dielectric Loss	44
4.13.1 Power Factor.....	45
4.14 Polar Molecules.....	45
4.15 Nonpolar Materials.....	45
4.16 Other Electrical Characteristics of Materials.....	45
4.16.1 Ferroelectricity.....	45
4.16.2 Piezoelectricity	47
4.17 Use of Dielectrics.....	48
4.18 Semiconductor Materials.....	48
4.19 Electrons and Holes in an Intrinsic Semiconductor (Pure Semiconductor)	49
4.20 Extrinsic Materials.....	49
4.20.1 n-type Material	49
4.20.2 p-type Material	50
4.21 Charge Densities in a Semiconductor	50
4.22 Electrical Properties of Semiconductors.....	51
4.22.1 Conductivity.....	51
4.22.2 Intrinsic Concentration.....	51
4.22.3 Energy Gap.....	51
4.22.4 Mobility	51
4.23 Hall Effect	51
4.23.1 Applications of Hall Effect	52
4.24 Thermistors	52
4.25 Photoconductors	52
<i>Objective Brain Teasers</i>	53

Chapter 5

Magnetic Properties of Materials..... 56

5.1 Introduction.....	56
5.2 Magnetic Parameters.....	56
5.2.1 Magnetic Dipole Moment	56
5.2.2 Magnetisation.....	56
5.2.3 Magnetic Susceptibility.....	57
5.3 Classification of Magnetic Materials.....	57
5.3.1 Diamagnetic Substance	58
5.3.2 Paramagnetic Substances	59
5.3.3 Ferromagnetic Substances.....	59
5.3.4 Antiferromagnetic Substances	61
5.3.5 Ferrimagnetic Substances	61
5.4 Curie Temperature	62
5.5 Laws of Magnetic Materials.....	63
5.5.1 Curie Law	63
5.5.2 Curie-Weiss Law	63
5.5.3 Neel Law	63
5.6 Domain Theory	64
5.7 Magnetisation Curve and Magnetic Hysteresis Loop.....	65
5.8 Soft Magnetic Materials.....	66
5.9 Hard Magnetic Materials	68
5.10 Magnetic Storage.....	70
<i>Objective Brain Teasers</i>	70

Chapter 6

Ceramics 72

6.1 Introduction.....	72
6.2 Silicate Ceramics.....	73
6.2.1 Silica.....	75
6.2.2 Feldspars.....	75
6.3 Material Preparation	75
6.3.1 Dry Pressing.....	76
6.3.2 Isostatic Pressing.....	76
6.3.3 Hot Pressing.....	76
6.3.4 Slip Casting	76
6.3.5 Extrusion.....	77
6.4 Thermal Treatments	77
6.4.1 Drying and Binder Removal.....	78
6.4.2 Sintering.....	78
6.4.3 Vitrification.....	78

6.5	Electrical Properties of Ceramics	78
6.6	Mechanical Properties	79
6.7	Thermal Properties of Ceramics	80
6.8	Glass	80
6.9	Carbon	81
6.9.1	Diamond	82
6.9.2	Graphite	82
6.9.3	Fullerenes	83
	<i>Objective Brain Teasers</i>	83

Chapter 7

Polymers.....85

7.1	Introduction	85
7.2	Basic Definitions	85
7.2.1	Polymers	85
7.2.2	Mer	85
7.2.3	Monomer	85
7.2.4	Polymerisation	86
7.2.5	Degree of Polymerisation	86
7.3	General Characteristics of Polymer	86
7.4	Molecular Structure of Polymers	87
7.4.1	Linear Chain Structure	87
7.4.2	Branched Chain Structure	87
7.4.3	Crosslinked Structure	88
7.5	Classification of Plastics	88
7.5.1	Thermoplastics	88
7.5.2	Thermosetting Plastics	88
7.6	Thermoplastic Materials	89
7.6.1	Polythelene	89
7.6.2	Polyvinyl Chloride (PVC)	89
7.6.3	Teflon	89
7.6.4	Polystyrene	90
7.7	Thermosetting Materials	90
7.7.1	Phenol Formaldehyde (PF) or Bakelite	90
7.7.2	Polyester	91
7.7.3	Melamine	91
7.7.4	Epoxies	91
7.8	Mechanical Behaviour of Plastics	92
7.9	Compounding Materials	92
7.10	Comparison of Polymers with Ceramics and Metals	93
	<i>Objective Brain Teasers</i>	93

Chapter 8

Composites94

8.1	Introduction	94
8.2	General Characteristics of Composites	94
8.3	Particle-reinforced Composites	96
8.3.1	Large-particle Composites	96
8.4	Fibre-Reinforced Composites	98
8.4.1	Continuous and Aligned Fibre Composites	99
8.4.2	Discontinuous and Aligned Fibre Composites	99
8.5	Laminar Composites	99
8.5.1	Sandwich Structures	99
8.6	Polymer-Matrix Composites (PMCs)	100
8.6.1	Glass Fibre-Reinforced Polymer (GFRP) Composites	100
8.6.2	Carbon Fibre-Reinforced Polymer (CFRP) Composites	100
8.6.3	Aramid Fibre-Reinforced Polymer Composites	101
	<i>Objective Brain Teasers</i>	101

Chapter 9

Mechanical Properties of Materials ... 103

9.1	Introduction	103
9.2	Normal Stress	103
9.3	Strain	104
9.4	Tension Test for Mild Steel	104
9.4.1	Specifications of Specimen	104
9.4.2	Stress Strain Curve for Tension	104
9.4.3	Actual Curve v/s Engineering Curve in Tension	105
9.4.4	Compression Curve for Mild Steel	105
9.4.5	Stress-strain Curve for other Grades of Steel in Tension	106
9.4.6	Stress-strain Curve for Various Materials in Tension	106
9.5	Common Terms of Mechanical Properties	106
9.6	Failure of Materials in Tension and Compression	112
9.6.1	Ductile Metals in Tension Test	112

9.6.2	Brittle Metals in Tension Test	112
9.6.3	Ductile Metals in Compression Test.....	112
9.6.4	Brittle Metals in Compression Test	112
9.7	Fracture.....	112
9.8	Hooke's Law	113
9.8.1	Assumption in Hooke's Law	113
9.9	Elastic Constants	113
9.9.1	Relationship between Elastic Constants	114
9.10	Difference between Linearly and Non-linearly Elastic Materials.....	114
	<i>Objective Brain Teasers</i>	115

Chapter 10

Ferrous Metals 117

10.1	Introduction.....	117
10.2	Pig Iron.....	117
10.3	Cast Iron.....	118
10.3.1	Forms of Carbon in Cast Iron	118
10.3.2	Grey Cast Iron	118
10.3.3	White Cast Iron.....	119
10.3.4	Malleable Cast Iron	120
10.3.5	Nodular Cast Iron	120
10.3.6	Alloy Cast Iron.....	121
10.4	Wrought Iron	121
10.5	Steel	122
10.5.1	Classification of Carbon Steel with Percentage of Carbon.....	122
10.5.2	Alloy Steel	123
10.5.3	Effect of Alloying Elements on Carbon Steels.....	124

10.6	Special Alloys Steels	124
10.6.1	Stainless Steels	124
10.6.2	High Speed Steels	124
10.6.3	High Temperatures Resisting Alloys	125
10.6.4	Magnetic Steels.....	125
10.6.5	Cryogenic Steels.....	125
	<i>Objective Brain Teasers</i>	125

Chapter 11

Non-Ferrous Metals and Alloys 127

11.1	Introduction.....	127
11.2	Aluminium.....	128
11.2.1	Uses of Aluminium	128
11.2.2	Limitation of Aluminium in Power Cables..	129
11.3	Aluminium Alloys.....	129
11.3.1	Duralumin	129
11.3.2	Y-alloy	129
11.3.3	Hindalium.....	130
11.3.4	Magnelium.....	130
11.4	Copper	130
11.4.1	Brasses	131
11.4.2	Bronze	132
11.4.3	Differences between Brass and Bronze ..	133
11.5	Lead	134
11.6	Tin	134
11.7	Nickel	134
11.8	Magnesium	135
11.9	Titanium	135
11.10	Tungsten.....	135
	<i>Objective Brain Teasers</i>	136



4.1 Introduction

- One of the principal characteristics of materials is their ability (or lack of ability) to conduct electrical current. Indeed, materials are classified by this property, i.e., they are divided into conductors, semiconductors and nonconductors (insulators or dielectrics). The conductivity, σ , of different materials at room-temperature spans more than 25 orders of magnitude. Moreover, when we take into consideration the conductivity of superconductors, measured at low temperatures, into consideration, this span extends to 40 orders of magnitude (taking an estimated conductivity for superconductors of about $10^{20} (\Omega\text{-cm})^{-1}$). We may note that this is the largest known variation in a physical property and is comparable to the ratio between the diameter of the universe ($\sim 10^{26}$ m) and the radius of an electron (10^{-14} m).

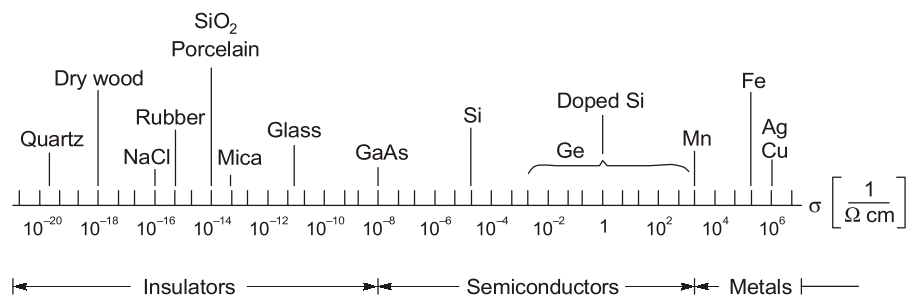
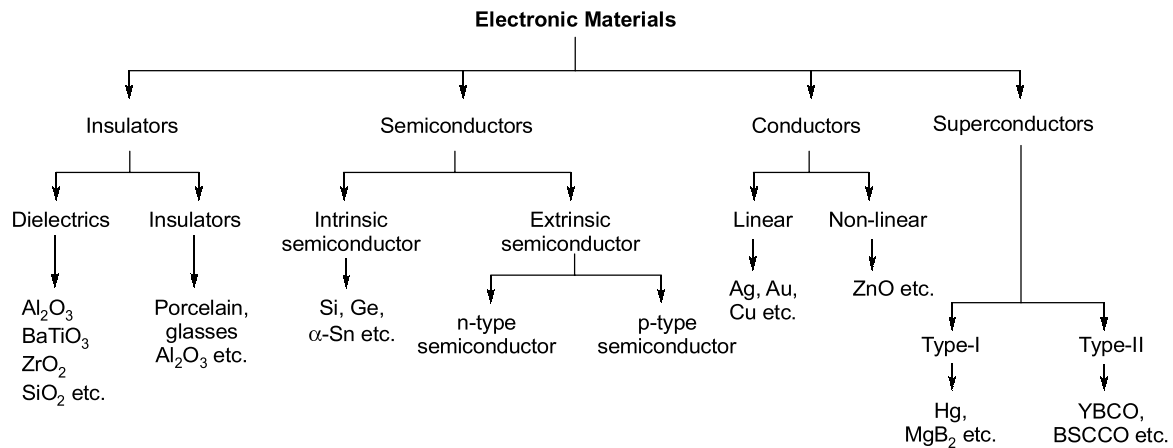


Fig. 4.1 Room-temperature conductivity of various materials. (Superconductors, having conductivities of many orders of magnitude larger than copper, near 0 K, are not shown. The conductivity of semiconductors varies substantially with temperature and purity). The reciprocal of the ohm (Ω) is defined 1 siemens (S).

- Electronic materials include insulators, semiconductors, conductors, and superconductors. This family of materials has revolutionized the entire world. From spark plugs made from alumina and copper wires for transmission of electric power to components for wireless communications, high power magnets used in Magnetic Resonance Imaging (MRI), capacitors, insulators, solar cells, active matrix displays, silicon and gallium arsenide based computer chips, electronic materials are found in numerous applications.
- Recent advances in materials have led to several breakthroughs in the development of new electronic materials. We now have ceramics that are not just excellent insulators, but also semiconductors and superconductors. Similarly, we have polymers which exhibit semiconducting and also superconducting properties. A simple and broad classification of some of the electronic materials is shown below.



4.2 Ohm's Law and Electrical Conductivity

- Ohm's law relates the current I (Ampere, A) or time rate of charge passage to the applied voltage V (Volt, V) as follows:

$$V = IR$$

where R is the resistance (Ohm, Ω)

- The units for V , I and R are respectively, volts (J/C), amperes (C/s), and Ohms (V/A).
- This law is applicable to most but not all materials.
- The value of R is influenced by specimen configuration and for several materials is independent of current. The resistance (R) of a resistor is a characteristics of the size, shape and properties of the materials used and expressed as

$$R = \frac{\rho l}{A} = \frac{l}{\sigma A}$$

where,

' l ' is the length (m) of the resistor i.e., the distance between the two points at which the voltage is measured.

' A ' is the cross-sectional area (m^2) perpendicular to the direction of current.

' ρ ' is the electrical resistivity ($\Omega\text{-m}$)

' σ ' which is the reciprocal of ' ρ ', is the electrical conductivity [$(\Omega\text{-m})^{-1}$].

Note: The magnitude of resistance depends upon the dimensions of resistor, as well as microstructure and composition of the material.

- The electrical conductivity (σ) is used to specify the electrical character of a material. It is reciprocal of the resistivity, i.e.,

$$\sigma = \frac{1}{\rho}$$

- Thus resistivity or conductivity allows one to compare different materials. Resistivity is a microstructure sensitive property.
- In addition to Ohm's law may be expressed as

$$J = \sigma E$$

where,

' J ' (A/m^2) is the current density (I/A) i.e., the current per unit area of specimen.

' E ' is the electric field intensity or the voltage difference between the two points divided by the distance (l) separating them, i.e.,

$$E = \frac{V}{l}$$

- One can also determine the current density (J) as

$$J = nq\bar{v}$$

where

' n ' is number of charge carriers (carriers/ m^3)

' q ' is the charge on each carrier ($1.6 \times 10^{-19}C$)

\bar{v} is the average drift velocity (m/s) at which charge carriers move.

- Thus, we have

$$\sigma E = nq\bar{v}$$

or

$$\sigma = nq \frac{\bar{v}}{E}$$

- The term $\frac{\bar{v}}{E}$ is the **mobility** of carriers and denoted by μ (m^2/V -sec). In the case of metals μ is the mobility of electrons.

- We have, $\mu = \frac{\bar{v}}{E}$

Thus, we have

$$\sigma = nq\mu$$

Here q is the charge.



Remember

- The electrical conductivity of materials can be controlled by
 - (i) Controlling the number of charge carries in the materials.
 - (ii) Controlling the mobility or ease of movement of the charge carriers.
- We may note that the mobility is particularly important in metals, whereas the number of carriers is more important in semiconductors and insulators.

- Charge carriers in metals are electrons, whereas charge carriers in semiconductors are both electrons and holes. Expression for conductivity gets modified for semiconductor as below.

$$\sigma = nq\mu_n + pq\mu_p$$

where μ_n and μ_p are the mobilities of electrons and holes respectively. The terms n and p represents the concentrations of free electrons and holes in a semiconductor.

- Electrical conductivity of materials varies tremendously (Table 4.1).

Table 4.1 Electrical conductivity of materials

Material	Conductivity ($\text{ohm}^{-1}, \text{cm}^{-1}$)	Material	Conductivity ($\text{ohm}^{-1}, \text{cm}^{-1}$)
Superconductors		Semiconductors	
Hg, Nb ₃ Sn,	Infinite (under certain conditions such as low temperatures)	Group 4B elements	
YBa ₂ Cu ₃ O _{7-x}		Si	5×10^{-6}
MgB ₂		Ge	0.02
		α -Sn	0.9×10^5