M.Tech. in Functional Materials

Introduction

Metallurgical and Materials Engineering is an interdisciplinary branch that deals with converting raw materials into a product by leveraging upon design, extraction, processing, and characterization of materials for aerospace, automotive, energy, electronics, and healthcare applications. The following are the focus areas of the Department: (a) Computational Materials Engineering, (b) Structural Materials, (c) Functional Materials, and (d) Process Metallurgy. Computational Materials Engineering provides an understanding of materials from atomistic to macro length scale and leads to smart and intelligent materials selection, alloy design, the discovery of unknown materials as well as improvement of metallurgical processes. The major focus of the Structural Materials area is to understand the processing-microstructure-property correlation for designing and processing materials with superior combinations of properties in the finished engineering products. Functional Materials possess one or more native properties that can be triggered by an external stimulus (electric/magnetic fields). Hence these materials are used for a plethora of functional devices ranging from energy harvesting, healthcare, and modern-day information technology. Process Metallurgy deals with mineral beneficiation and metal extraction.

The Department offers an M.Tech. program and an M.Tech.-Ph.D. dual degree program in Materials Engineering. Incoming students choose a specialization from the following four specializations at the beginning of their first semester: (a) Computational Materials Engineering, (b) Structural Materials, (c) Functional Materials, and (d) Process Metallurgy. The credits required for the M.Tech. degree are distributed among the program core, specialization core, specialization electives, program electives, open electives, project, and non-graded compulsory activities. The program core courses are common among all specializations and cover the core concepts within the discipline of Materials Engineering. The student will take the specialization core courses and the specialisation elective courses offered in the chosen specialization and conduct a project within that specialization. The specialization core courses provide the essential background of the chosen specialization and prepare the students for the specialization electives as per their options exercised. The program elective courses in the program structure are designed to ensure sufficient breadth in Materials Engineering, and these courses must be chosen from the other specializations within the program. The open elective courses allow students to explore courses from any department. Previously, the course curriculum for the Structural Materials, and Process Metallurgy specializations was presented. Here, the course curriculum for Functional Materials is presented.

1. **Objectives**

- Provide rigorous academic and research training in advanced areas of Functional Materials Engineering.
- Produce professionals with an in-depth understanding of Materials Engineering, capable of providing solutions to meet future materials challenges.
- A further objective of the program is to inculcate certain specific enabling skill-sets to prepare the students to take up challenges in any one or more functional materials domains viz. (i) Academics, (ii) Applied Research, (iii) Research & Development, (iv) Materials Engineering & Technology, (v) Entrepreneurs, (vi) Industry and (vii) Innovators.

2. **Graduate attributes**

- In-depth understanding of the fundamental concepts of Functional Materials.
- Knowledge to characterize functional materials features at various length scales using experimental and computational approaches.
- Ability to apply the acquired knowledge of Functional Materials to real-world engineering problems.
- Skills to demonstrate and investigate intrinsic properties of Functional Materials by the use of experimental techniques.
- Ability to design, fabricate and characterize device structures such as semiconductor devices, sensors, etc.
- Skills to understand and solve industry-oriented problems and challenges.
- Skills to effectively communicate scientific findings to peers and the general public.
- Innovative skills to analyse, design, and execute technical projects.

- Appreciation and adherence to professional ethics.

3. Learning Outcome

Ability to

- Synthesise and characterize functional materials
- Understand the structure-property correlation of functional materials
- Understand, design, control, and fabricate Functional Materials devices, synthesis processes, their properties, and applications.
- Define a research problem and devise an appropriate methodology for addressing the same.
- Identify normative commitments of technological knowledge, artifacts, and familiarity with the manifold responsibilities linked to their profession.
- Critically develop linguistic competence and subject competence in the genres of technical communication.

Program structure with courses

Cat.	Course Number	Course Title	L-T-P-D	Credits		Cat.	Course Number	Course Title	L-T-P-D	Credits
I Semester						**II Semester**				
MC	MTL7XX0	Computational Thermodynamics and Kinetics of Materials	3-0-2-0	4		MC	MTL7XX0	Structure and Characterization of Materials	3-0-2-0	4
MC	MTL7XX0	Industry 4.0: Applications in Metallurgical and Materials Engineering	2-0-0-0	2		SC	MTL7XX0	Specialisation Core-2	3-0-0-0	3
SC	MTL7XX0	Specialisation Core -1	3-0-0-0	3		SC	MTL7XX0	Specialisation Core-3	0-0-2-0	1
SE	MTL7XX0	Specialisation Elective-1	3-0-0-0	3		SE	MTL7XX0	Specialisation Elective-3	3-0-0-0	3
SE	MTL7XX0	Specialisation Elective-2	3-0-0-0	3		SE	MTL7XX0	Specialisation Elective-4	3-0-0-0	3
NH	HSN7XX0	Technical Communication	1-0-0-0	0		NH	HSN7XX0	Innovation and IP Management	1-0-0-0	0
Total				**15**		Total				**14**
III Semester						**IV Semester**				
SE	MTL7XX0	Specialisation Elective-5	3-0-0-0	3		OE		Open Elective-2	3-0-0-0	3
SE	MTL7XX0	Specialisation Elective-6	3-0-0-0	3		MP	MTD7XX0	Project (Stage-II)	0-0-0-11	11
OE		Open Elective-1	3-0-0-0	3		NH	HSN7XX0	Professional Ethics	1-0-0-0	0
MP	MTD7XX0	Project (Stage-I)	0-0-0-5	5						
NH	HSN7XX0	Systems Engineering and Project Management	1-0-0-0	0						
Total				**14**		Total				**14**

Distribution of Credits (M.Tech.)

S.No.	*Category*	*Category Title*	*Total Credits*
1	MC	Program Core	10
2	SC	Specialisation Core	7
3	SE	Specialisation Elective	**12 (18)**
4	ME	Program Electives	**6 (0)**
5	OE	Open Electives	6
6	MP	Project	16
7	NH	Non-Graded Compulsory	4
Total (Graded)			**57**
Total (Graded + Non-graded)			**61**

M.Tech. Program Courses

List of Program Core courses

Course Number	***Course Title***	***L-T-P-D***	***Credits***
MTL7XX0	Computational Thermodynamics and Kinetics of Materials	3-0-2-0	4
MTL7XX0	Structure and Characterization of Materials	3-0-2-0	4
MTL7XX0	Industry 4.0: Applications in Metallurgical and Materials Engineering	2-0-0-0	2

List of Specialisation Core courses

(a) Functional Materials

Course Number	***Course Title***	***L-T-P-D***	***Credits***
MTL7XX0	Functional Materials	3-0-0-0	3
MTL7XX0	Symmetry, Structure, and Tensor Properties	3-0-0-0	3
MTP7XX0	Functional Materials Laboratory	0-0-2-0	1

List of Specialisation Elective courses

List of specialisation elective courses to be offered for M.Tech. students under different specializations:

(a) Functional Materials

Course Number	***Course Title***	***L-T-P-D***	***Credits***
MTL7XX0	Functional Materials for Sensors and Actuators	2-0-2-0	3
MTL7XX0	Fundamental of Scintillation Detector Materials	3-0-0-0	3
MTL7XX0	Functional 2D Materials	2-0-2-0	3
MTL7XX0	Advanced Transmission Electron Microscopy	2-0-2-0	3
MTL7XX0	Metamaterials	1-0-0-0	1
MTL/BBL 7XX0	Biomimetic Materials	3-0-0-0	3
MTL/PHL 7XX0	Processing and Engineering Application of Magnetic Materials	3-0-0-0	3
MTL/PHL 7XX0 (1 fractal from each dept.)	Materials for Electrochemical Energy Conversion and Storage	2-0-0-0	2
MTP/PHP 7XX0	Design and Fabrication of Printed Circuit Board	0-0-2-0	1
MTL/PHL 7XX0	Advanced Ferroic Materials	3-0-0-0	3
MTL/EEL 7XX0	Advanced Semiconductor Materials and Device Applications	2-0-2-0	3

Courses from Other Departments			
PH8LXX0	Vacuum Systems and Thin Film Technology	3-0-0-0	3
PH8LXX0	Semiconductor Device Technology	3-0-0-0	3
PHL7XX0	Solar Energy Technologies	3-0-2-0	4
MEL7XX0	MEMS & Microsystems Technology	3-0-2-0	4
MEL7XX0	Nanosensors	3-0-0-0	3
CHL7XX0	Catalytic Nanomaterials	3-0-0-0	3
CHL7XX0	Packaging of Electronic Devices – Polymeric materials & Chemical Technology	3-0-2-0	4
CHL7XX0	Structure & Property for Polymers	3-0-0-0	3
CYL6530	Nanomaterials and Nanodevices	2-0-2-0	3
CYL6XX0	Advanced Electrochemistry and Applications	3-0-0-0	3
BBL7XX0	Bioenergy Systems	3-0-0-0	3
BBL7XX0	Tissue Engineering & Medical Devices and Implants	3-0-0-0	3
EEL7XX0	Non-Volatile Memory Technologies	2-0-0-0	2

Program Elective courses

A student from a given specialisation should opt for Program Elective courses from the other Specialisation courses (core and elective).

Open Elective courses

The open elective courses can be taken from courses offered by any Department.

Functional Materials Core Courses

Title	**Functional Materials**	Number	MTL7XX0
Department	Metallurgical and Materials Engineering	L-T-P [C]	3-0-0 [3]
Offered for	M.Tech.	Type	Specialization Core
Pre-requisite			

Objectives

1. To provide the students with a detailed understanding (synthesis/growth, structure, and properties) of the functional materials.
2. To develop an understanding of the usage of functional materials as a component of modern devices.

Learning Outcomes

The students will be able to:

1. Compare, correlate and investigate the different synthesis, characterization, and application of exemplar functional materials.
2. Integrate the understanding of functional materials' properties and their applications.

Contents

Material synthesis and processing of functional materials: Bulk Synthesis: Solid state synthesis, Sol-Gel synthesis, Thin-Film synthesis: Sputtering, Molecular beam epitaxy, CVD, 3D printing, electrospinning. *(8 lectures)*

Defects in solids: Defect types and dimensionality effect on defects, Characterization (morphological and spectroscopic), Control of defects. *(8 lectures)*

Semiconductor materials: Band structure, Doping, Band-Gap engineering. *(2 lectures)*

Applications: Beyond Si semiconductors, GaN, GaAs, SiC, Ga_2O_3, LEDs, and photovoltaic cells (CdS, CIGS, CZTS, Perovskites and Organic solar cell materials). *(6 lectures)*

Materials for energy applications: Thermoelectric materials: ZT value, Band-Gap, Conductivity engineering, Oxide materials, Heusler alloys, Artificial and hierarchical materials, Peltier cooling, Thermoelectric generator, , Dielectric, Piezoelectric, Ferroelectric materials and applications,. *(8 lectures)*

Magnetic materials & applications: Magnetic exchange energy, anisotropy energy, Magnetic domains, Application of soft and hard magnetic materials, Magnetic data storage, , Superconductors in electronics. *(6 lectures)*

Optical materials: , Optical lithography, and applications, Electro-optic materials. *(4 lectures)*

Textbook

1. Askeland, D.R., Phule, P.P., Wright, W.J., *The Science and Engineering of Materials*, 6th edition, Cengage Learning, 2010.
2. Callister, W.D., Rethwisch, D.G., *Materials science and Engineering: An Introduction*, 8th edition, Wiley, 2010.
3. Mitchell, B.S., *An Introduction to Materials Engineering and Science for Chemical and Materials Engineers*, 1st ed., Wiley- Interscience, 2003.
4. Kittel, C., *Introduction to Solid State Physics*, 8th edition, Wiley, 2005.

Reference Books

1. Kasap, S.O., *Principles of Electronic Materials and Devices*, 3rd edition, McGraw-Hill, 2006.
2. Raghavan, V., *Materials Science & Engineering: A first course*, 5th edition, PHI Learning, 2004.

Online Course Material

1. Haridoss, P., *Physics of Materials*, NPTEL Course Material, Department of Metallurgy & Material Science, Indian Institute of Technology Madras, https://nptel.ac.in/courses/113/106/113106039/.

2. Garg, A., *Electroceramics*, NPTEL Course Material, Department of Material Science & Engineering, Indian Institute of Technology Kanpur, https://nptel.ac.in/courses/113/104/113104005/.

Title	**Symmetry, Structure and Tensor Properties**	**Number**	MTL7XX0
Department	Metallurgical and Materials Engineering	L-T-P [C]	3–0–0 [3]
Offered for	M.Tech.	Type	Specialization Core
Pre-requisite	Linear Algebra and Matrix Mathematics, MATLAB/Mathematica		

Objectives

1. Introduce the concept of symmetry in crystal lattices, point groups, and space groups.
2. Use of symmetry in the tensor representation of crystal properties, including anisotropy, representation surfaces, elasticity, and applications to piezoelectricity.

Learning Outcomes

The students will be able to:

1. Learn how to calculate different thermodynamic properties of different materials.
2. Understand how crystalline anisotropy affects/governs the property anisotropy.

Contents

Introduction: Spherical trigonometry and Applications in crystallography. *(5 lectures)*

Crystal lattices: Direct lattice, Crystal systems, Bravais lattice. *(2 lectures)*

Point groups: Stereographic projection, Proper cubic point groups, Improper point groups (dihedral angle, inversion symmetry), Types of point groups: 2D and 3D lattices. *(7 lectures)*

Space groups: Enumeration of the operations, Different space groups with specific materials examples. *(7 lectures)*

Group theory: Basic Concepts, Character Tables, Examples, Symmetry and Lattice Vibrations: Mode of Vibrations, Jahn-Teller Effect. *(7 lectures)*

Tensor properties of materials: Basic tensorial operations, Transformation of axis, Eulerian angles, Orthogonality Neumann principle, Pseudo tensors, Symmetry and Mathematical properties of tensors. *(7 lectures)*

Different ordered tensors: 2nd order (Stress-Strain, Permittivity, Permeability, Thermal Expansion), 3rd order (Piezoelectricity), 4th order (Elasticity Tensor). *(7 lectures)*

Textbook

1.Newnham, R.E., *Structure-property relations* (Vol. 2). Springer Science & Business Media, 2012.
2. Nye, J.F., *Physical properties of crystals: their representation by tensors and matrices*. Oxford university press, 1985.

Reference Books

1. Buerger, M.J., *Elementary crystallography*, John Wiley & Sons, 1956.
2. International Tables for Crystallography Volume A: Space-group symmetry, ISBN: 978-0-470-68575-4.

Online Course Material

1. Wuensch, B., *Symmetry, Structure, and Tensor Properties of Materials*, DMSE MIT, MIT OCW, https://ocw.mit.edu/courses/materials-science-and-engineering/3-60-symmetry-structure-and-tensor-properties-of-materials-fall-2005/syllabus/.

Title	**Functional Materials Laboratory**	Number	MTP7XX0
Department	Metallurgical and Materials Engineering	L-T-P [C]	0-0-2 [1]
Offered for	M.Tech.	Type	Specialization Core
Pre-requisite			

Objectives
1. To introduce different kinds of functional material synthesis (thin film and bulk) techniques, as well as an insight into device fabrication.
2. Introduce different functional property measurement techniques and concomitant analysis.

Learning Outcomes
The students will be able to:
1. Get first-hand knowledge of synthesizing functional materials and device fabrication.
2. Understand different types of measurement techniques and analyse the device performance.

Laboratory Experiments
1. Performance evaluation of capacitors by electrochemical impedance spectroscopy.
2. Performance evaluation of secondary batteries by electrochemical impedance spectroscopy.
3. Fabrication and property evaluation of dielectric/ ferroelectric ($BaTiO_3$/PZT) materials.
4. Electrode preparation (Thin-Film deposition) via spin coating.
5. Synthesis of 2D materials and their hybrids(e.g, graphene, MoS2).
6. Magnetic measurements (M-H hysteresis/ M vs T measurement).
7. Semiconductor characterization: Hall/ I-V measurements.
8. Optical Property measurements: Transmittance/ Photoluminescence/ Band-Gap.
9. Performance evaluation of alkaline primary cell/ lead-acid battery/ Li-ion batteries.
10. 3D Printing of electronic material/bio-materials/energy materials.

Textbook
1. Cheong, K.Y., Impellizzeri G., Fraga M. A., *Emerging Materials for Energy Conversion and Storage*, 1st Edition, Elsevier, 2018.
2. Banks, C., E., Browson, D., A., C., *2D Materials, Characterization, Production and Applications*, CRC Press, 2017.
3. Schroder, D.K., *Semiconductor Material and Device Characterization,* 3rd ed., Wiley-Interscience, New York, 2006.
4. Venuvinod, P.K., Ma W., *Rapid prototyping: laser-based and other technologies*. Springer Science & Business Media, 2013.
5. Gibson, I., Rosen, D., Stucker, B., *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*, Springer, New York, NY, 2015.
6. Kumar, L. J., Pandey, P.M., Wimpenny, D.I., eds. *3D printing and additive manufacturing technologies*. Singapore: Springer, 2019.

Self-Learning Materials
1. Lab manuals and study materials will be provided for Hall, I-V measurements, M-H hysteresis, M vs T measurement, spin coater, electrochemical impedance spectroscopy and 3D printing.

Online Course Material
1. Ramanathan, S., Chemistry and Biochemistry, IIT Madras, https://nptel.ac.in/courses/104/106/104106105/.
2. Maiti, H.S., Department of Metallurgy and Material Science, IIT Kharagpur, https://nptel.ac.in/courses/113/105/113105015/.
3. Bhat, K.N., Anathasuresh, G.K., Gopalakrishnan, S., Vinoy, K.J., Department of Mechanical Engineering, IISc Bangalore, https://nptel.ac.in/content/storage2/courses/115103039/module16/lec38/2.html.

4. Ganguli, A.K., Department of Nanotechnology, IIT Delhi, https://nptel.ac.in/courses/118/102/118102003/. 5. Banerji, P., Department of Metallurgy and Material Science, IIT Kharagpur. https://nptel.ac.in/courses/113/105/113105025/. 6. Majumder, S.B., Material science Centre, IIT Kharagpur, https://nptel.ac.in/courses/113/105/113105102/. 7. Kapil, S., Department of Mechanical Engineering, IIT Guwahati, https://onlinecourses.nptel.ac.in/noc21_me115/preview.

DETAILED SYLLABUS FOR THE SPECIALISATION ELECTIVE COURSES

Title	**Functional Materials for Sensors and Actuators**	Number	MTL7XX0
Department	Metallurgical and Materials Engineering	L-T-P [C]	2-0-2 [3]
Offered for	M.Tech./Ph.D.	Type	Specialization Elective
Pre-requisite			

Objectives
1. To understand the basics of sensors, actuators materials, and their operating principle.
2. To explain the working of various types of electrochemical sensors and actuators.

Learning Outcomes
The students will be able to:
1. Apply the knowledge for the selection of appropriate materials for sensing, design, and device fabrication.
2. Understand the design and device fabrication challenges.

Contents
Fractal-1: Sensor Materials and its Applications: Introduction of sensors, Basics of energy transformation and differences between transducers, Sensors and Actuators, Principles of micro sensors, basics of semiconducting metal oxide–based gas sensors. *(7 lectures)*

Conducting polymers sensor materials, mechanism of sensing, properties and their applications, magnetic nanoparticles sensors, gas sensing materials: Transition metal oxides, SiC, 2D materials their hybrids and heterostructures, Materials for Biosensing, FET based biosensors and luminescent materials for biosensing. *(7 Lectures)*

Fractal-2: Actuator Materials and its Applications: Introduction of actuators and its working principle, Piezoelectric Actuators: Resonant and Non-Resonant actuation, Bimorphs, Figure of merit, Group III-V nitrides (GaN/AlN), Electrochromic and Electroactive Polymer actuators: Wet and Dry Electroactive polymer actuators (EAP) actuators, material selection, design and fabrication of actuators. *(7 lectures)*

Shape memory alloys (SMAs): Introduction of Shape memory alloy materials, design of SMAs, figure of merit (FOM), Scaling laws, magnetic actuators: Magnetostriction, Magnetostrictive materials: giant magnetostriction, Design and Control of magnetostrictive actuators, Scaling laws *(7 lectures)*

Lab:
1) Synthesis of functional materials (graphene oxide, boron nitride) for application in gas sensing (MT).
2) Fabrication of gas sensor (graphene oxide/ other 2D materials) (MT).
3) Characterization using spectroscopic technique (UV-Visible) and Quality control (MT).
4) Synthesis of metal (gold/silver/glass substrate) nanoparticles for biosensing (MT).
5) Fabrication and characterization (Raman Spectroscopy) of biosensor (MT).
6) Characterization using spectroscopic technique (UV-Visible) and Quality control (MT).
7) Synthesis of PVDF for application in polymeric sensing (MT).
8) Characterization using spectroscopic technique (UV-Visible) and Quality control (MT).
9) Fabrication of polymer sensor (Universal Testing Machine) (MT).
10) Synthesis of carbonaceous material for electrochemical sensing (MT).
11) Fabrication of electrochemical sensor (Three-Electrode System) (MT).
12) Characterization using spectroscopic technique (UV-Visible) and Quality control (MT).

Textbook
1. Kloeck, B., Rooji, N.F., *Mechanical Sensors in semiconductor Sensors*, John Wiley NY 1994.
2. Silva, D., Clarence W., *Sensors and actuators: Engineering system instrumentation*. CRC Press, 2015.

Reference Books
1. Rupitsch, Johann, S., *Piezoelectric Sensors and Actuators*. Springer-Verlag Berlin Heidelberg, Heidelberg, 2018.

Online Course Material

1. Pandya, H.J., Department of Electrical & Electronic Engineering IISc Bangalore NPTEL Course Material, https://www.youtube.com/watch?v=nE1C4ghfvac&list=PLgMDNELGJ1CbufZjqWa8uoSlQWKqVwPN7.

Title	**Fundamental of Scintillation Detector Materials**	Number	MTL7XX0
Department	Metallurgical and Materials Engineering	L-T-P [C]	3-0-0 [3]
Offered for	M.Tech, PhD	Type	Specialization Elective
Pre-requisite			

Objectives

1. A fundamental understanding of various scintillation detectors materials, and their characteristics.

Learning Outcomes

Upon completion students are expected to

1. Get a general overview of scintillation detectors
2. Have an insight into the scintillator material composition, critical elements, and usage.

Contents

Introduction, Scintillation detector basics, Components of a scintillation detector, Detection efficiency –Density factor, Detection efficiency –Thickness Factor, Total detection efficiency, Energy transfer/interaction in scintillating materials, Properties of ideal scintillation materials. Cross scintillation mechanism, Organic scintillators– Liquid organic, Plastic, Loaded organic, Response of organic scintillators. *(14 lectures)*

Inorganic scintillators – Scintillation mechanism, Glass scintillators, Scintillator gases, Radiation damage effects in inorganic scintillators, Nanoscintillator – Structural effect, Surface effect, dielectric confinement, Form of nanoscintillators – Nanoparticles, Thin-Films, Nano-Ceramics. Photomultiplier tubes and photodiodes: Photocathodes – Photoemission, Spontaneous electron emission, Spectral response, Fabrication, Statistics of electron multiplication, Photomultiplier tube characteristics, Silicon photo multiplier. *(14 lectures)*

Photodiodes – Advantages, Conventional, Avalanche, Charge coupled devices, Radiation spectroscopy with scintillators: General considerations in gamma ray spectroscopy, Properties of scintillation gamma ray spectrometers, Characterization of scintillating materials, Customizing scintillation detector – Tradeoffs on materials, Sizes and Components, Specialized detector configurations based on scintillation – Phoswich detector, Moxon-Rae detector, Position sensitive scintillators. *(14 lectures)*

Textbook

1. Knoll, G.F., *Radiation and Detection,* 4^{th} edition, ISBN: 0470131489, 2010.

Reference Books

1. Korzhik, M., Gektin, A., *Engineering of Scintillation Materials and Radiation Technologies: Proceedings of ISMART*, Springer, ISBN: 978-3-319-68465-9, 2016.
2. Yanagida, T., *Inorganic scintillating materials and scintillation detectors*, Proc Jpn Acad Ser B Phys Biol Sci. 9, 94(2): 75–97. Doi: 10.2183/pjab.94.007, 2018.
3. Duclos, S., *Ceramic Scintillators*, Annual Review of Materials Science, 27, 69-88, 1997.

Title	**Functional 2D Materials**	Number	MTLXXX0
Department	Metallurgical and Materials Engineering	L–T–P [C]	2–0–2 [3]
Offered for	M.Tech., PhD	Type	Specialisation Elective
Pre-requisite			

Objectives

1. To introduce the emergent field of functional 2D materials.
2. Provides a comprehensive overview of 2D materials their hybrids and heterostructures systems that are relevant to different scientific applications.

Learning Outcomes

Upon completion, students are expected to

1. To know the basics of 2D materials.
2. Van der Waal and Non- van der Waal materials hybrids and heterostructures.
3. Design and fabricate 2D Advanced Materials based devices.

Contents

Fundamentals of 2D Materials

Introduction of functional quantum materials, 2D family, Electronic, Magnetic, Optical properties of functional quantum materials, Dirac metals, Weyl fermions. *(5 lectures)*

2D functional quantum materials at atomic scale, Topological insulators, Computation of electronic properties of functional quantum materials, Investigation of defect and Ohmic/Schottky contacts. *(5 lectures)*

Fundamental and properties of two-dimensional materials in sensing: Introduction, Band Alignment, Parameters of sensor performance. *(4 lectures)*

Fabrication of Devices, Application and Challenges

Synthesis (top-down and bottom-up approach and challenges), Characterization, and transfer of Van der Waals (graphene, boron nitride, Molybdenum disulphide, Tungsten Disulphide, Black Phosphorus, etc.) atomic sheets, Microscopic characterization by TEM. *(3 lectures)*

Non-Van der Waals Materials (Borophene, Hematene, Plumbene, MXene, etc.) their Hybrids (2D/1D, 2D/2D, 2D/3D), composites and heterostructures, Fabrication of 2D Material devices and challenges. *(3 lectures)*

Application of 2D Materials and their hybrids as well as heterostructures: Introduction (Graphene, Xenes, MXene, and Complex 2D Materials) Opto-Electronics (LEDs), Gas Sensor, Bio-Sensor, Drug-Delivery, Filtration/Desalination, Photovoltaics, Energy Storage and Generation, Lubricants, Environmental Remediation. *(6 lectures)*

Challenges with 2D Materials hybrids/heterostructures and device fabrications. *(2 lectures)*

Lab:

1) Synthesis of Van der Waals 2D material (e.g. Graphene, TMDCs) atomic sheets.
2) Characterization (morphological and spectroscopic) of the atomic sheets.
3) Fabrication of nano-devices (bio sensors, gas sensors, etc.).
4) Failure analysis and Quality control.
5) Synthesis of non-Van der Waals 2D material (e.g. Hematene, borophene, etc.) atomic sheets.
6) Characterization (morphological and spectroscopic) of the atomic sheets.
7) Fabrication of nano-devices (bio sensors, gas sensors, etc.).
8) Failure analysis and Quality control.
9) Synthesis of 2D hybrids and heterostructres (e.g. graphene/graphene oxide/reduced graphene oxide/borophene/hematene/TMDCs, etc.) atomic sheets.

10) Characterization (morphological and spectroscopic) of the atomic sheets.
11) Failure analysis and Quality control.

Textbook

1. Zettilli, N., Gubernatis, J.E., Lookman, T., *Quantum Mechanics: Concepts and Applications, Wiley*, 2009.
2. Griffiths, D.J., *Introduction to quantum mechanics*, Prentice Hall International, 2004.
3. Banks, C., E., Browson, D.A.C., *2D Materials, Characterization, Production and Applications*, CRC Press, 2017.

Reference Books

1. Ng, L.W.T., Hu, G., Howe, R.C.T., Zhu, X., Yang, Z., Jones, C., Hasan, T., *Printing of Graphene and Related 2D Materials: Technology, Formulation and Applications*, Springer, 2019.
2. Errana, G., *Metal Oxide Nanostructures as Gas Sensing Devices,* CRC Press, 2012.
3. Avouris, P., Heinz, T.F., Low, T*., 2D Materials Properties and Devices*, Cambridge University Press, 2017.

References

1. Paglione, J., Butch, N.P., Rodriguez, E. E., *Fundamentals of Quantum Materials: A Practical Guide to Synthesis and Exploration,* World Scientific Pub Co Inc, 2021.
2. Heitmann, D., Quantum Materials*, Lateral Semiconductor Nanostructures, Hybrid Systems and Nanocrystals,* Springer, 2010.
3. Bartolomeo, D., *2D Materials and Van der Waals Heterostructures,* MDPI, ISBN 978-3-03928-769-7, https://doi.org/10.3390/books978-3-03928-769-7.
4. Hywel, M., Rout, C.S., Late, D.J., *Late Fundamentals and Sensing Applications of 2D Materials,* Elsevier, 2021.

Title	**Advanced Transmission Electron Microscopy**	Number	MTL7XXX0
Department	Metallurgical and Materials Engineering	L–T–P [C]	2–0–2 [3]
Offered for	M.Tech., PhD	Type	Specialization Elective
Pre-requisite			

Objectives

1. Introduce the working principle of Transmission Electron Microscopy (TEM).
2. Introduce of advanced TEM techniques to understand the material characterization at the atomic scale.

Learning Outcomes

The students will be able to:

1. Develop an understanding of TEM from an experimental and theoretical perspective.
2. The basic and advanced TEM simulation techniques for atomic-scale High Resolution (Scanning/TEM) imaging.

Contents

Introduction of advanced techniques in TEM: Aberration correction in TEM, Z & Phase contrast, High angle annular dark field imaging, Electron Magnetic Circular Dichroism (EMCD). (*4 lectures*)

4D-Scannning Transmission Electron Microscopy (4D-STEM), Electron Energy Loss Spectroscopy (EELS). (*3 lectures*)

Cryo-Electron microscopy, Electron tomography, Lorentz microscopy, Holography in TEM, Differential phase contrast. (*7 lectures*)

Computational aspect of advanced TEM techniques: Multislice simulation of high-resolution TEM imaging, Phase and Z contrast imaging. (*4 lectures*)

Simulation methods for advanced TEM techniques e.g., EMLD, EMCD, 4D-STEM, EELS. (*3 lectures*)

Advanced concept of digital micrograph scripting, Simulation of differential phase contrast imaging, EELS data processing and analysis in TEM (*7 lectures*)

TEM simulation

1) Indexing of electron diffraction pattern.
2) Simulation of electron diffraction pattern.
3) Simulation of High-Resolution (HR-TEM) images.
4) Simulation of Scanning Transmission Electron Microscope (STEM) images in TEM.
5) Simulation of Electron Energy Loss Spectroscopy (EELS) spectra.
6) Basics of digital micrograph scripting (installation and environment setting).
7) Processing HR-TEM images by digital micrograph scripting.
8) Processing EELS, STEM image data by digital micrograph scripting.

Textbook

1. Kirkland, E.J., *Advanced computing in electron microscopy*, Springer, ISBN:978-1-4419-6533-2, 2020.
2. Landup, D., *Data visualization in python with pandas and matplotlib*, ISBN:13: 979-8521342877, 2020.

Reference Books

1. Brent, F., James, H., Transmission Electron Microscopy and Diffractometry of Materials. Springer, Berlin. ISBN 978-3-642-29760-1 (2013).

Title	**Metamaterials**	Number	MTL7XXX
Department	Metallurgical and Materials Engineering	L–T–P [C]	1–0–0 [1]
Offered for	B.Tech., B.Tech-M.Tech Dual Degree, M.Tech., PhD	Type	Specialisation Core
Pre-requisite			

Objectives

1. This course introduces the student to the field of metamaterials.

Learning Outcomes

1. The students will learn fundamental concepts underlying physical properties and fabrication techniques of metamaterials.
2. The students will be exposed to the various application of metamaterials.

Contents

Introduction to metamaterials and Meta surfaces. *(2 lectures)*

Optical and mechanical metamaterials, Micro-/Nano-fabrication methodologies, and Prospective applications. *(3 lectures)*

Sub-wavelength waveguiding and focusing, Super-resolution imaging and nano-lithography beyond the diffraction limit of the light, Negative refraction and permeability and Invisibility cloaking. *(5 lectures)*

Plasmonic metamaterials, Enhanced Raman scattering, Extraordinary transmission, Light-trapping for solar cell. *(4 lectures)*

Textbook

1. Choudhury, P.K., *Metamaterials: Technology and Applications*, CRC Press, Taylor & Francis Group, 2021.

Reference Books

1. Simovski, C., Tretyakov, S., *An Introduction to Metamaterials and Nanophotonics*, Cambridge University Press, 2020.
2. Cui, T.J., Smith, D., Liu, R., *Metamaterials: Theory, Design, and Applications*, Springer Publications, 2009.

Title	**Biomimetic Materials**	Number	MTL7XX0
Department	Metallurgical and Materials Engineering, and, Bioscience and Bioengineering	L-T-P [C]	3–0–0 [3]
Offered for	M.Tech., PhD	Type	Specialization Elective
Pre-requisite			

Objectives

1. Introduces to evolution aspects of materials design in nature.
2. Provide knowledge to design and fabricate bio-inspired materials.

Learning Outcomes

The students are expected to:

1. Understanding the design of bioinspired materials.
2. Knowledge to fabricate synthetic model systems whose structural organization resembles those of natural materials.

Contents

Fundamentals of engineering in biological materials: Biological engineering principles, Self - assembly, Hierarchy, Adaption, Evolution and Convergence, Basic building blocks found in biological materials. *(8 lectures)*

Functional biological materials: Adhesion and Attachment, Surfaces and Surface properties, Optical properties, Cutting: Sharp biological materials, Functional adaptation, Self-healing. *(6 lectures)*

Bioinspired structures: Aerospace and Automobile, Architecture and Building designs, Fibre optics and Micro-lenses, Manufacturing. *(7 lectures)*

Bioinspired materials: Superhydrophobic Materials: The Lotus leaf effect, Self-healing materials, Energy, Artificial photo-synthesis. *(7 lectures)*

Water purification, Attachment devices and Bio-inspired adhesives, Tough ceramic composites Biomedical applications. *(7 lectures)*

Molecular based biomimetics: Self-assembly nano-structures, Virus-assisted synthetic Materials, Genetically engineered peptides for inorganics, Diatom-derived MEMS devices. *(7 lectures)*

Textbook

1. Meyers, M.A., Chen P.Y., *Biological Materials Science - Biological Materials, Bioinspired Materials and Biomaterials*, Cambridge University Press, 2014.

2. Fratzl, P., Dunlop, J.W.C., Weinkamer, R., *Materials Design Inspired by Nature: Function Through Inner Architecture*, The Royal Society of Chemistry, 2013.

Self-Learning Material

Studart, A.R., Libanori, R., Erb, R.M., *Functional Gradients in Biological Composites in Bio- and Bioinspired Nanomaterials*, Wiley-VCH Verlag GmbH & Co. KGaA, 2014.

Title	**Processing and Engineering application of Magnetic Materials**	Number	MTL7XX0
Department	Metallurgical and Materials Engineering and Physics	L–T–P [C]	3–0–0 [3]
Offered for	M.Tech., PhD	Type	Elective
Pre-requisite	Basic knowledge on Quantum Mechanics		

Objectives

1. The course will provide knowledge of the underlying phenomena of magnetism.
2. Emphasis will be on the preparation process & characterization methods of magnetic materials used for engineering applications.

Learning Outcomes

The students are expected to have:

1. The ability of understanding magnetic phenomena, and the metallurgical aspect of developing magnetic materials.
2. They will also get exposure to engineering application of magnetic methods and magnetic materials.

Contents

Fractal-1: Fundamentals of Magnetism

Origin of magnetism, Bohr magnetron, Magnetic field and their calculation, Susceptibility and Permeability, Energy associated with the magnetic field, Thermodynamics of magnetic field, Magnetic forces, Spin orbit coupling, Crystal field. *(4 lectures)*

Classification of magnetic materials, Weiss molecular field, Exchange interaction, Magnetic anisotropy, Domains, Domain wall and domain wall motion, Magnetic hysteresis and Barkhausen emissions, Techniques for characterization of magnetic materials, Magnetic transport property, Magnetostriction, Magnetocaloric effect. *(10 lectures)*

Fractal-2: Processing and application of Soft and Hard Magnetic Materials

Nickel Iron alloys, Cobalt-Iron alloys, Electrical steel (CRNO, CRGO), Rapid solidification and amorphous electrical steel, Amorphous & Nanostructured magnetic alloys, Soft ferrites, Microstructure and magnetic property co-relations. *(6 lectures)*

Hard Magnetic Materials: Alnico, NdFeB, SmCo, MnBi, Hard ferrites. *(5 lectures)*

Heusler alloys and their applications. *(3 lectures)*

Fractal-3: Processing and application of Magnetic thin films and nanomaterials

Deposition of magnetic thin films and multilayers, Magnetic energy of thin film materials, Characterisation of magnetic thin films. *(3 lectures)*

Magnetic coupling in thin films, spin valve structure, Giant magneto resistance and tunneling magneto resistance, sensors. *(5 lectures)*

Magnetic wires and needles, Magnetic nanoparticles, Superparamagnetism, Quantum dots and molecular magnets, 2-D magnets. *(3 lectures)*

Application of magnetic nanomaterials in Biology and sustainable technology. *(3 lectures)*

Textbook

1. Chen, C.W., *Magnetism and Metallurgy of Soft Magnetic Materials* (Dover Books on Physics), Courier Corporation, 2013.
2. Cullity, B.D., Graham, C.D., *Introduction to Magnetic Materials*, 2nd Edition, Wiley, 2009.
3. Coey, J.M.D., *Magnetism and Magnetic Materials*, Cambridge University Press, 2010.

Reference Books

1. Jiles, D., *Introduction to magnetism and magnetic materials*, Chapman and Hall, 1991.
2. Chikazumi, S., *Physics of Ferromagnetism*, 2^{nd} Edition, OUP Oxford, 2009.

Title	**Materials for Electrochemical Energy Conversion and Storage**	Number	MTL/PHL 7XX0
Department	Metallurgical and Materials Engineering and Physics (1 fractal each)	L-T-P [C]	2-0-0 [2]
Offered for	M.Tech., PhD	Type	Specialization Elective
Pre-requisite			

Objectives
The instructor will:
1. Provide the student with extended knowledge of the basic principles and recent advances in Energy Storage materials and associated technologies for consumer electronics to high-power applications.
2. Provide the students with the role of materials in energy storage technologies.

Learning Outcomes
The students are expected to gain knowledge on:
1. Different modes of energy conversion, and storage with respect to scale, cost, energy, and power density.
2. Structure processing property performance relationship of the energy materials developed over time.

Contents
Fractal-1: Batteries
Introduction: Overview of electrochemical energy storage and conversion devices, Classification, Applications. *(2 lectures)*

Batteries: Introduction to batteries, Primary and secondary batteries, Solid-state and liquid electrolyte batteries, Lead acid batteries, Nickel cadmium batteries, Li-ion and Li-Polymer batteries, Intercalation and Conversion materials, Battery capacity and Life, Micro-batteries, Thin-Film batteries, Materials for high-energy density 2D and 3D batteries. *(12 lectures)*

Fractal-2: Fuel Cells and Supercapacitors
Fuel cells: Principle and types, Performance characteristics and Efficiency of fuel cell, Proton exchange fuel cells, Solid oxide fuel cells, Types of solid oxide fuel cells: High and Intermediate temperature, Single chamber solid oxide fuel cells, Polymer electrolyte fuel cells, Acid/alkaline fuel cells, Phosphoric acid fuel cell, Molten carbonate fuel cell, Fuel cell stack, Hydrogen storage. *(10 lectures)*

Supercapacitors: Difference between capacitor and supercapacitor, Electrolyte and Electrode materials, Electric double layer capacitors, Challenges and Applications. *(4 lectures)*

Textbook
1. Cheong, K.Y., Impellizzeri G., Fraga M.A., *Emerging Materials for Energy Conversion and Storage*, 1st Edition, Elsevier, 2018.

Reference Books
1. Rosen, M. A., *Energy Storage*, Nova, 2012.

Online Course Materials
1. Bazant, M., MIT open course ware: Electrochemical Energy Systems, MIT Course Number 10.626/10.426,
https://ocw.mit.edu/courses/chemical-engineering/10-626-electrochemical-energy-systems-spring-2014/.
2. Pal, K., *Selection of Nanomaterials for Energy Harvesting and Storage Application*, NPTEL Course Material, Mechanical Engineering, Indian Institute of Technology Roorkee,
https://nptel.ac.in/courses/112/107/112107283/.

Title	**Design and Fabrication of Printed Circuit Board**	Number	MTP/PHP 7XX0
Department	Metallurgical and Materials Engineering and Physics	L-T-P [C]	0–0–2 [1]
Offered for	M.Tech., PhD	Type	Specialization Elective
Pre-requisite			

Objectives

1. To develop students' skills and understanding of working on the Printed Circuit Board (PCB).
2. Hands-on training of lithography patterns on various substrates (Polyethylene terephthalate (PET) and flame retardant (FR-4)).

Learning Outcomes

The students will be able to:

1. Design and fabricate printed circuits board circuits on flexible and non-flexible substrates.
2. Understand different kinds of PCBs, the difference between Printed Wiring Boards (PWB) and PCB, types of PCBs: Single Sided (Single Layer), Multi-Layer (Double Layer), PCB Materials.
3. Understand all the fabrication processes and challenges.

Contents

1. Design of mask (L-edit, etc.).
2. Fabrication of electrodes (two/four, interdigitated and micro-heater).
3. Characterization of flexible/non-flexible PCB substrate.
4. Process and Quality control.
5. Over, Under etching (Wet/Dry) and Failure analysis.
6. Rounding effect.
7. Fabrication of complex circuits on flexible substrates.
8. Multilayer PCB design.

Textbook

1. Mack, C., *Fundamental Principles of Optical Lithography: The Science of Microfabrication*, ISBN:9780470018934, DOI:10.1002/9780470723876, 2007.

Self-Learning Material

1. Lee, J.H., Mechanical and Industrial Engineering, University of Massachusetts (UMass) Amherst, Metamaterials Blog,
https://www.youtube.com/channel/UCct3ViUapJ8jRBzxxWVxtyA/videos.

Title	**Advanced Ferroic Materials**	Number	MTL/PHL 7XX0
Department	Metallurgical and Materials Engineering and Physics	L-T-P [C]	3-0-0 [3]
Offered for	M.Tech., PhD	Type	Specialization Elective
Pre-requisite			

Objectives
1. Provide an in-depth understanding of functional ferroic materials.
2. Introduce advanced present-day topics on functional ferroic materials.

Learning Outcomes
The students will be able to:
1. Carry out modern day scientific research in the field of functional ferroic oxides.
2. Follow and critique the scientific papers as well as carry out advanced analysis.

Contents
Introduction: Basic symmetry consideration of materials, Introduction to specific materials, Thermodynamics: Maxwell's equations for different functional properties. *(3 lectures)*

Classical definition: Structural phase transitions in ferroelectrics, Landau theory of phase transition (disordered and displacive), Concept of order parameter, Landau theory for phenomenological calculations of properties, Morphotropic Phase boundaries, Mean-field theory and soft mode concept. *(11 lectures)*

Concepts of ferroelectric domains in bulk: Coexisting domain states, Twinning operations, Domain wall orientation, Imaging of domains, Static domain patterns: Equilibrium domain patterns, Domain patterns connected with phase boundaries. *(3 lectures)*

Dynamic properties of domains walls in bulk: Switching properties, Ferroelectric & Piezoelectric hysteresis loop, Switching phenomena and Small-Signal response: Overview of switching mechanisms, Domain wall motion, Theories of single wall motion, Defect pinning and creep of domain walls, Switching process in selected materials, Theory and Modelling of switching, Rayleigh loops, Extrinsic contribution to small-signal dielectric signals. *(11 lectures)*

Relaxors, Aging and Fatigue properties in Ferroic materials. *(4 lectures)*

Multiferroic materials: Analogies and Differences between ferroelectrics and ferromagnets, Applications, Scarcity of multiferroics, Magnetoelectric coupling. *(6 lectures)*

Measurement techniques: Ferroelectric measurements, Piezoelectric, Pyroelectric and Multiferroics measurement techniques. *(4 lectures)*

Textbook
1. Lines, M.E., Glass, A.M., *Principles and Applications of Ferroelectrics*, Clarendon Press, Oxford, 1977.
2. Rabe, K. M., Ahn, C.H., Triscone, J.M., *Physics of Ferroelectrics: A Modern Perspective*, Springer, Berlin, 2007.
3. Alexander, T.K., Cross, L.E., Fousek, J., *Domains in ferroic crystals and thin films*. Vol. 13. New York, Springer, 2010.

Reference Books
1. Scott, J.F., *Ferroelectric memories*. Vol. 3. Springer Science & Business Media, 2000.
2. Newnham, R.E., *Structure-property relations* (Vol. 2). Springer Science & Business Media, 2012.
3. Wadhawan, V.K., *Introduction to Ferroic Materials*, Gordon and Breach, Amsterdam, 2000.

Title	**Advanced Semiconductor Materials and Device Applications**	Number	MTL 7XX0
Department	Metallurgical and Materials Engineering and Electrical Engineering	L-T-P [C]	2-0-2 [3]
Offered for	M.Tech./Ph.D.	Type	Specialization Elective
Pre-requisite			

Objectives
1. To develop an understanding of the layered and non-layered semiconductor materials synthesis/growth and characterization techniques used in the semiconductor industry.

Learning Outcomes
The students will be able to:
1. Understand the basics of advanced semiconductor materials properties, failure analysis methods, reliability, and characterization.
2. Fabricate semiconductor layered material devices and analyse their properties.

Contents
Fractal-1: Material Synthesis and Characterization

Introduction, Basics of semiconductor, Crystallographic properties of the semiconductors. *(7 lectures)*
Growth and synthesis of semiconductor materials (2D and 3D), Defects and its characterization and Advantages of 2D materials. *(7 lectures)*

Fractal-2: Device Characterization

Electrical characterization of semiconductors: Material influenced test structure based electrical characterization methods like: two-probe/four-probe, Van der Pauw method, Hall-effect measurements etc. *(5 lectures)*

Characterization of junctions and diodes: C-V measurements, Life-time measurement, Metal-semiconductor: Schottky contacts, Barrier-height measurement, I-t techniques. *(5 lectures)*

Reliability and failure analysis: Gate oxide reliability measurement, Time-to-breakdown and charge to breakdown and Failure analysis, Noise measurements and analysis. *(4 lectures)*

Lab:
1) Synthesis of semiconductor materials atomic sheets of Graphene Oxide (MT).
2) Synthesis of semiconductor elemental sheets of Xenes and Transition metal dichalcogenides (TMDCs) (MT).
3) Fabrication of p-n junction (Graphene/Si/SiO_2, G/MoS_2, etc.) (MT).
4) Characterization of p-n junction (Graphene/Si/SiO_2, G/MoS_2, etc.) (MT).
5) Electrical characterization of the fabricated devices (EE).
6) Reliability and Failure analysis (EE).
7) Material process (spectroscopic) and Quality control (MT).
8) Tailoring the electrical, optical and Youngs' modulus of the semiconducting materials (MT).
9) Application of semiconductor in sensing (SERS/gas/strain) (MT/EE).
10) Application of semiconductor in opto-electronics (MT/EE).

Textbook
1. Schroder, D.K., *Semiconductor Material and Device Characterization,* 3rd edition, Wiley-Interscience, New York, 2006.
2. Nicollian, E.H., Brews, J., *MOS Physics and Technology,* ISBN: 978-0-471-43079-7, 1982.

Online Course Material

1. Haridoss, P., *Physics of Materials*, NPTEL Course Material, Department of Metallurgy & Material Science, Indian Institute of Technology Madras,
https://nptel.ac.in/courses/113/106/113106039/.
2. Parasuraman, S., *Fundamentals of electronic materials and devices*, NPTEL Course Material, Department of Metallurgy & Material Science, Indian Institute of Technology Madras,
https://nptel.ac.in/courses/113/106/113106039/.