Materials Science & Engineering

Mission Statement
The Institute of Materials Science & Engineering (IMSE) seeks to create and sustain a culture of interdisciplinary materials science research and education at Washington University that eliminates traditional boundaries between departments and schools. Toward this end, the IMSE administers an interdisciplinary PhD program; expands and administers user facilities and resources for materials processing and characterization; coordinates and provides management support for interdisciplinary groups pursuing external funding for campus-wide research efforts; and coordinates research and entrepreneurial interactions with industry and national facilities.

About IMSE
Throughout history, civilization has advanced as a result of new innovations in materials that enabled the development of new technologies. Indeed, the solutions to the significant challenges that we currently face, including finding new sources of energy, developing ways to use the available energy more efficiently, and addressing environmental concerns, demand the development of new materials. The design of new materials is also important for medical advances, with further developments in tissue engineering being only one example. Furthermore, many new techniques developed in materials investigations have expanded uses; one example is the application of methods for characterizing the structures of complex materials to study disease propagation.

Materials Science & Engineering is the interdisciplinary field focused on the development and application of new materials with desirable properties and microstructures. Disciplines in the physical sciences (chemistry, physics, etc.) and engineering fields (mechanical engineering, electrical engineering, biomedical engineering, etc.) frequently play a central role in developing the fundamental knowledge that is needed for materials studies. The discipline of Materials Science & Engineering integrates this knowledge and uses it to design and develop new materials and to match these with appropriate technological needs.

While the development of materials is moving at a faster pace today than ever before, the current "time to market" from discovery to deployment of new materials is still too slow; it can take 20 years or more to develop, optimize, validate, and insert a material into service. Recognizing the bottleneck that the availability of new materials places on innovations in other strategic areas, in 2011 the White House launched the Materials Genome Initiative (MGI) to fund the growth of the national materials innovation infrastructure, including experimental and computational tools and collaborative networks, necessary to both accelerate and bring down the cost of materials discovery and development.

The Institute of Materials Science & Engineering (IMSE) is well positioned to address the challenges articulated by the MGI. Established in 2013, the IMSE brings together more than 30 research groups in Arts & Science, the School of Engineering & Applied Sciences, and the Medical School. The IMSE works to integrate and expand the existing materials interests at Washington University by establishing and overseeing shared research and instrument facilities, creating partnerships with industry and national facilities, and setting up outreach activities. In addition, IMSE oversees an interdisciplinary PhD program in Materials Science & Engineering that exploits the full potential of the existing materials activities to educate the next generation of materials scientists and engineers.

Current focused areas of research and advanced graduate education within the IMSE include:

Plasmonics, Photonics and Materials for Sensors and Imaging
Fabricating nanoscopic metallic and dielectric structures has become feasible with the maturity of nanofabrication techniques. When carefully engineered, these nanostructures can act as enhanced optical filters tuned to filter and/or amplify spectral-polarization signatures of the incoming light. The monolithic integration of various nanostructures with CMOS technology can open up realization of compact sensors with enhanced sensing capabilities. These sensors can be used to identify the spectral-polarization signatures of healthy vs. tumor cells during in-vivo sensing, such as endoscopy, laparoscopy and other medical related imaging. Other applications for these sensors include: enhanced and non-invasive blood glucose monitoring, blood oxygen level monitoring and others. Furthermore, these sensors can be used for non-invasive medicine, where seamless integration with today's smartphone technology can help monitor the health of the general population in a cost-effective manner.

Computational Materials Science
Computational Materials Science tools, based in chemistry and physics, give us: (i) Qualitative frameworks for thinking about atomistic processes and mechanisms, (ii) Quantitative understanding of thermodynamic driving forces, and (iii) Prediction of properties or molecular architectures for engineering design. Often, we will want to know the structure of a few atoms in a material (e.g., defect or reactive sites), and quantum mechanics allows us to calculate these structures and associated electronic energies to high accuracy. However, we ultimately need to predict multiscale properties that can be compared with experimental data, so we use statistical mechanics to perform temporal or spatial averages over a large number of simulations to obtain these macroscopic observables. We thus develop predictive insight that may be used to guide experimental design of new materials.
Energy Harvesting and Storage

Energy is the underpinning of all technological progress our society makes. Tapping into energy sources and converting and storing energy into useful forms are challenges humans face within the constraints of limited natural resources and an increasing global demand. Materials lie at the heart of this challenge. By creating novel materials with unique structure, properties and better processes, scientists and engineers in IMSE are creating exciting opportunities to address the grand energy challenge.

Materials for Regenerative Medicine

The IMSE Materials for Regenerative Medicine research concentration comprises two areas:

• Synthesis of bio-inspired materials
• Understanding the material properties of tissues and biomaterials

Structure, Properties and Phase Transformations of Complex Materials

Combining an impressive array of properties, including extraordinary tensile strength (~2-4 GPa), large elastic deflections (~2% elastic strain), and excellent wear and corrosion resistance, bulk metallic glasses (BMG) have been touted as revolutionary structural materials for more than a decade. Indeed, they have been implemented in a number of “boutique” applications, such as military weapons systems and sporting goods. Recently, focus has turned to BMGs’ remarkable ability to be thermoplastically formed into complex shapes easily and inexpensively in the supercooled liquid regime, a capability traditionally limited to low-strength plastics. This combination of both outstanding mechanical properties and ease of processing opens the door for BMGs to truly become the transformational materials they promised to be. However, the lack of long-range atomic order in these alloys both dictates their unique mechanical behavior and processing characteristics and presents a challenge for understanding the relationships among structure, processing, and properties in BMGs within a consistent physical framework. Further, a quantitative understanding of the process by which liquids become glasses remains elusive. Research in this area is focused on these questions for glasses and the complex crystal and quasicrystal phases to which they are related.

Environmental Technologies and Sustainability

Materials science intersects with the fields of environmental science and sustainability in a variety of ways. This involves both developing new materials and conducting basic science research to understand processes governing the behavior of the materials. Specific research areas with emphasis in IMSE include: carbon dioxide capture and conversion (to metal carbonates and other products), treatment for removal of aqueous-phase contaminants, and the surface chemistry of environmental materials from natural and engineered systems.

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Director

Kenneth F. Kelton
Arthur Holly Compton Professor of Arts & Sciences - Physics
PhD, Harvard University

Associate Director

Katharine M. Flores
Professor and Associate Chair (Materials Science) - Mechanical Engineering & Materials Science
PhD, Stanford University
Professor Flores’ primary research interest is the mechanical behavior of structural materials, with particular emphasis on understanding structure-processing-property relationships in bulk metallic glasses and their composites.

Professors

Sophia E. Hayes
Professor - Chemistry
PhD, University of Califomia, Santa Barbara
Physical inorganic chemistry; materials chemistry; solid-state NMR; magnetic resonance; Optically-pumped NMR (OPNMR); semiconductors; quantum wells; magneto-optical spectroscopy; Quadrupolar NMR of thin films and tridecameric metal hydroxide clusters and thin films; Carbon capture, utilization and storage (CCUS); CO2 geosequestration; CO2 capture; in situ NMR; metal carbonate formation.
Lan Yang
Edwin H. & Florence G. Skinner Professor - Electrical & Systems Engineering
PhD, California Institute of Technology
Professor Yang's research interests are fabrication, characterization, and fundamental understanding of advanced nano/micro photonic devices with outstanding optical properties. Currently, her group focuses on the silicon-chip based ultra-high-quality micro-resonators made from spin-on glass. The spin-on glass is a kind of glass obtained by curing a special liquid using sol gel or wet chemical synthesis to form a layer of glass. The main advantage of the spin-on glass is the easy tailoring of the nano/micro structure of the glass by controlled variation in the precursor solutions. It enables them to fabricate various micro/nano photonic devices from advanced materials with desired properties.

**Associate Professors**

Young-Shin Jun
Harold D. Jolley Career Development Associate Professor - Energy, Environmental & Chemical Engineering
PhD, Harvard University
Professor Jun's research is highly interdisciplinary as the Jun group seeks to enable more environmentally sustainable CO2 sequestration as a mitigation technique for climate change. The group also develops nanochemistry-enabled new treatment techniques and catalysts for purifying drinking water and remediating contaminated water and soil, benefiting water reuse, managed aquifer recharge, and reverse osmosis processes. In addition, the ENCL investigates biomineralization and bio-inspired chemistry for novel materials development.

Srikanth Singamaneni
Associate Professor - Mechanical Engineering & Materials Science
PhD, Georgia Institute of Technology
Professor Singamaneni's research interests include Plasmonic engineering in nanomedicine (in vitro biosensing for point-of-care diagnostics, molecular bioimaging, nanotherapeutics), photovoltaics (plasmonically enhanced photovoltaic devices), surface enhanced Raman scattering (SERS) based chemical sensors with particular emphasis on the design and fabrication of unconventional and highly efficient SERS substrates, hierarchical organic/inorganic nanohybrids as multifunctional materials, bioinspired structural and functional materials, polymer surfaces and interfaces, responsive and adaptive materials and scanning probe microscopy and surface force spectroscopy of soft and biological materials.

**Assistant Professors**

Parag Banerjee
Assistant Professor - Mechanical Engineering & Materials Science
PhD, University of Maryland, College Park
Professor Banerjee's research interests focus on two aspects of materials science and engineering. Firstly, he is interested in the synthesis of nanomaterials with tunable properties using principles of self-assembly and self-limited reactions. Secondly and perhaps more importantly, he is interested in integrating these materials into "performance enhancing" nano-architectures for components such as biomedical sensors, energy storage and energy harvesting devices.

Mikhail Y. Berezin
Assistant Professor - Radiology
PhD, Moscow Institute of Oil and Gas / Institute of Organic Chemistry
My research interest lies in the investigation and application of molecular excited states and their reactions for medical imaging and clinical treatment. Excited states are the cornerstone of a variety of chemical, physical, and biological phenomena. The ability to probe, investigate, and control excited states is one of the largest achievements of modern science. The lab focuses on the development of novel optically active probes ranging from small molecules to nanoparticles, and the development of optical instrumentation for spectroscopy and imaging and their applications in medicine.

Julio D'Arcy
Assistant Professor - Chemistry
PhD, University of California, Los Angeles
The overarching goals of the D'Arcy laboratory are to discover and apply novel functional nanostructured organic and inorganic materials utilizing universal synthetic chemistry protocols that control chemical structure, nanoscale morphology, and intrinsic properties. We are interested in capacitive and pseudocapacitive nanostructured materials such as conducting polymers, metal oxides, and carbon allotropes possessing enhanced chemical and physical properties, i.e. charge carrier transport, ion transport, surface area, thermal and mechanical stability. Our concerted material discovery process is a multi-pronged approach; organic and inorganic nanostructured materials are synthesized via solution processing, electrochemistry, vapor phase deposition, and combinations thereof. Alternatively, we also develop self-assembly techniques that result in tailored materials.
Erik Henriksen
Assistant Professor - Physics
PhD, Columbia University
We are an experimental condensed matter research lab with interests primarily in the quantum electronic properties of graphene and other novel two-dimensional systems. We utilize state-of-the-art nanofabrication techniques in combination with measurements made at low temperatures and high magnetic fields to explore both the fundamental electronic structures and emergent quantum phenomena of low-dimensional materials.

Cynthia Lo
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, Massachusetts Institute of Technology
Professor Lo uses electronic structure calculations and molecular dynamics simulations to study the structure and reactivity of molecular and nanoscale systems for solar energy utilization. Some applications of current interest include bio-hybrid solar cells, photosynthesis, transparent conducting oxides for photovoltaic and thermoelectric applications, and multifunctional heterogeneous catalysts and photocatalysts. In addition, Professor Lo is interested in developing multiscale computational methods that link existing methods across time and length scales in order to model complex chemical systems.

Rohan Mishra
Assistant Professor - Mechanical Engineering & Materials Science
PhD, The Ohio State University
In his lab at WashU, Mishra plans to identify and develop a quantitative measure of structure-property correlations in materials, such as epitaxial thin films and materials with reduced dimensionality, using a synergistic combination of scanning transmission electron microscopy and atomic-scale theory, to create rational design of materials with properties tailored for electronic, magnetic, optical and energy applications.

Bryce Sadtler
Assistant Professor - Chemistry
PhD, University of California, Berkeley
The Sadtler research group seeks to understand and control structure-property relationships in adaptive, mesostructured materials. Through hierarchical design of the atomic composition, nanoscale morphology, and mesoscale organization of the individual components, we can direct the emergent chemical reactivity and physical properties of these complex systems. Research projects combine solution phase growth techniques to synthesize inorganic materials, external fields to control the growth and assembly of mesoscale architectures, and super-resolution imaging to provide spatiotemporal maps of the optical response and photocatalytic activity during the morphological evolution of these structures. Knowledge gained from these fundamental studies will be used to create functional materials, including plasmonic substrates that enhance absorption in thin-film semiconductors, mesostructured photocatalysts for solar fuels generation, and chemical sensors based on self-assembled photonic structures.

Simon Tang
Assistant Professor - Orthopaedics
PhD, Rensselaer Polytechnic Institute
With the overall theme of understanding the biological regulation of skeletal matrix quality, our research group integrates engineering and biology approaches for (1) understanding the effect of disease mechanisms on the structure-function relationships of skeletal tissues and (2) developing of translatable therapeutic and regenerative strategies for these diseases. The investigation of these scientific questions includes the application of finite element analyses, multiscale tissue mechanics, and the functional imaging of skeletal tissues for regenerative medicine with in vitro and in vivo biological systems.

Elijah Thimsen
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, Washington University
The Interface Research Group focuses on advanced gas-phase synthesis of nanomaterials for energy applications. We are currently exploring nonthermal plasma synthesis and atomic layer deposition (ALD). The goal is to discover and then understand useful interfacial phenomena. Examples of applications we are currently interested in are: transparent conducting oxides, photovoltaics, lithium-sulfur batteries and coatings for high-temperature combustion.
Fuzhong Zhang
Assistant Professor - Energy, Environmental & Chemical Engineering
PhD, University of Toronto
Professor Zhang’s research interests focus on developing synthetic biology approaches to produce advanced biofuels, chemicals, and materials from sustainable resources. Current research projects include: (1) developing dynamic regulatory systems for biosynthetic pathways; (2) engineering microbes to produce structure-defined biofuels and chemicals; (3) developing microbial factories for advanced materials; (4) engineering cyanobacteria for synthetic biology applications.

Degree Requirements
Interdisciplinary PhD in Materials Science & Engineering

To earn a PhD degree, students must complete the Graduate School requirements, along with specific program requirements. Course work includes:

4 IMSE Core Courses (12 academic credits)
  • Mechanical Behavior of Materials (MEMS 5601)
  • Introduction to Polymer Science & Engineering (MEMS 5608)
  • Quantitative Materials Science & Engineering (MEMS 5610)
  • Thermodynamics & Kinetics of Materials (Physics 537)
Solid State Chemistry or Physics (3 academic credits)
  • Solid State and Materials Chemistry (Chem 465)
  or
  • Solid State Physics (Physics 472)
IMSE First-Year Research Rotation (3 academic credits)
IMSE Seminar (1 academic credit; 2 required, 3 allowed for credit)
Two Electives from "Structures" or "Properties" categories below (p. 6) (6 credits)
Additional electives from participating departments to reach 36 academic credits (~9 academic credits, ~3 courses)
Students must maintain an average grade of B (GPA 3.0) for all 72 credits. Additionally, the required courses must be completed with no more than one grade below a B-.
Up to 24 graduate credits may be transferred with the approval of the Graduate Studies Committee, chaired by the Associate Director of the IMSE.

In addition to fulfilling the course and research credit requirements, the student must:
  • Complete a Research Rotation
  • Identify an IMSE faculty member willing and able to support their thesis research on a materials-related topic
  • Fulfill the Teaching requirement
    • Attend 2+ Teaching Center Workshops
    • 15 units of teaching experience (basic and advanced levels)
  • Successfully complete the Qualifying Examination (oral & written)
  • Maintain satisfactory research progress, as determined by the student's Thesis Advisor and Mentoring Committee
  • Successfully complete the Thesis Proposal and Presentation
  • Successfully complete and defend a dissertation
Failure to meet these requirements will result in dismissal from the program.

Course Plan
Year 1

Fall Semester (13 Credits)
  • Solid-State and Materials Chemistry (Chem 465) or elective
  • Quantitative Materials Science and Engineering (MEMS 5610)
  • Mechanical Properties of Materials (MEMS 5601)
  • Elective
  • IMSE Seminar

Spring Semester (13 Credits)
  • Thermodynamics/Kinetics of Materials (Physics 537)
  • Introduction to Polymer Science and Engineering (MEMS 5608)
  • Solid State Physics (Physics 472) or Elective
  • IMSE First-Year Research Rotation
  • IMSE Seminar Series

Summer
  • Begin thesis research
  • Prepare for Qualifying Exam (August)
    • Committee: 3 Core Faculty, must include representatives from Engineering and Arts & Science
    • Written document and oral presentation on research rotation, oral exam on fundamentals from core courses.

Years 2 and beyond
  • 3 Electives (Discuss with PhD Advisor)
  • IMSE Seminar (once more for credit)
  • IMSE PhD Research
  • Teaching requirement
    • Attend 2+ Teaching Center Workshops
    • 15 units of teaching experience (basic & advanced levels)
• Annual (or more frequent) meetings with Faculty Mentoring Committee
  • Committee: minimum of PhD Advisor & 2 Core Faculty
• Thesis proposal & presentation (fifth semester)
  • Committee: Advisor + 2 Core faculty + 2 other IMSE faculty + 1 outside IMSE
  • Committee must include representatives from Engineering and Arts & Science
• Dissertation & oral defense

Electives: Structure Category
MEMS 5603: Materials Characterization Techniques I
MEMS 5604: Materials Characterization Techniques II
Physics 539: Structure and Diffraction in Materials

Electives: Properties & Applications Category
BME 5231 Biomaterials Science: Polymer Physics
BME 523 Biomaterials Science
Chem 543 Physical Properties of Quantum Nanostructures
EECE Electrochemical Engineering
EECE 518 Aerosol Science and Technology
EECE 534 Environmental Nanochemistry
ESE 531 Nano and Micro Photonics
ESE 532 Introduction to Nano-Photonic Devices
EPSc 511 Minerals in Aqueous Environments
EPSc 580 Deformation of Planetary Materials
MEMS 5504 Fracture Mechanics
MEMS 5606 Soft Nanomaterials
MEMS 5607 Introduction to Polymer Blends and Composites
MEMS 5609 Electronic Materials Processing
MEMS 5611 Principle and Methods of Micro- and Nanofabrication
Physics 549 Solid State Physics I
Physics 550 Solid State Physics II
Physics 565 Magnetism & Superconductivity

Teaching Requirements
Students in the PhD program will receive formal pedagogical training by attending a minimum of two Teaching Workshops offered by the Washington University Teaching Center, and will be expected to fulfill a total of at least 15 units of teaching experience with at least 5 units at the basic level and 5 units at the advanced level. A unit of teaching is broadly defined as an hour spent communicating with a group of students or scholars. The teaching requirements must be completed before the student submits his or her doctoral dissertation to the graduate school.

For the basic-level teaching requirement, the following experiences qualify for 1 unit of teaching per event:
• Teach or co-teach a laboratory session
• Conduct an organized recitation or review section of a course

• Deliver a lecture in class using notes provided by the professor of the course
• Lead a journal club session
• Host an outreach activity such as preparing and presenting a lecture and/or demonstration in science at a middle or high school

For the advanced-level teaching requirement, the following experiences qualify for 1 unit of teaching per event:
• Prepare from scratch and deliver a lecture in an IMSE class
• Present a seminar giving the results of the student’s own research at an IMSE-wide seminar or at a national meeting. At least 1 unit must but no more than 5 units may be qualified in this fashion.

Five units of teaching at the basic level is a minimum. However, if possible, students are encouraged to have additional teaching units at this level, with 10 units being most desirable for teaching development. Each student must submit to the Graduate Studies Committee a form detailing how the teaching requirement was completed.

Research Rotations
During their first year, students are required to register for and complete one research rotation with IMSE faculty mentors (Core or Affiliate Faculty). A presentation and report on one of the research rotations will be an integral component of the qualifying exam. The rotations are chosen in consultation with the Associate Director of the IMSE (Director of Graduate Studies) and must be mutually agreeable to both the student and the mentor. At the completion of the rotation, the student must submit to the Associate Director a written report approved by the mentor.