Materials Processing Center

The Materials Processing Center (MPC) was established as an interdisciplinary center within the School of Engineering in response to a recognized national need to improve the materials processing knowledge base and to streamline the process of translating materials research results into industrial innovations and applications.

Following a science-to-systems approach, MPC assembles faculty resources and leverages existing knowledge to help companies and federal agencies address challenges and create opportunities. More than 60 faculty and senior research staff have active research accounts in MPC, and the center organizes events for the broader materials research community at MIT, which includes more than 190 faculty. MPC is now in its 31st year.

In the past year, MPC's research volume reached an all-time high of $16.7M, representing an increase of 23% over the previous year, and a total increase of 114% over the past two years. While this growth occurred across the interdisciplinary scope of the center's research, it included continued significant growth in research on materials for energy. MPC continued to support its two subcenters—the Solid State Solar Thermal Energy Conversion Center (S^3TEC) and the Microphotonics Center (MPhC)—as well as professor Harry Tuller's large multi-faculty program in chemomechanics of far-from-equilibrium interfaces, and professor Donald Sadoway's Advanced Research Projects Agency–Energy (ARPA–E) program, Electroville.

Four new research thrusts were also intiated in the MIT–Iberian Nanotechnology Laboratory (INL), and the center worked with the Microsystems Technology Laboratories to organize the first MIT–INL workshop, which will be held in Braga, Portugal, in July 2011. MPC also worked with professor Eugene Fitzgerald in his successful proposal for the fifth and final research thrust in the Singapore–MIT Alliance for Research and Technology Centre for research on low-energy electronic systems. This program will be managed by MPC over the next five years.

Industry Collegium and Industrial Advisory Board

The MPC Industry Collegium consists of 10 companies that provide direct financial support for the center's activities through annual donations. Representatives from these companies participate in MPC's annual Materials Day and related activities and work with MPC throughout the year to identify opportunities for collaboration. Current collegium members include: Belgium Consortium, Corning, Hitachi, Ishikawajima-Harimi Heavy Industries, Merck KGaA, Michelin, Raytheon, Siam Cement Public, Toyota, and Varian Semiconductor Equipment Associates. Growth of collegium membership is a high priority for MPC.

The MPC Industrial Advisory Board meets for a full day after the Materials Day event each year. MPC's director and staff report on the prior year's activities and describe planned initiatives and goals for subsequent years. In addition, several new faculty present their planned research, and selected senior faculty discuss major new programs.

The board provides valuable advice on program development and management and identifies opportunities for interactions with industry. The board meeting culminates in an oral and written report to the dean of the School of Engineering or a designated representative. Current board members represent 3M, Bell Laboratories North America, Draper Laboratory, General Motors, Lockheed Martin, Lord Corporation, Novartis Pharmaceuticals, Saint-Gobain, Solvay Advanced Polymers, and Varian Semiconductor Equipment Associates.

New faculty who spoke at this year's board meeting were: professors Mircea Dincă (Chemistry), Pedro Reis (Civil and Environmental Engineering), Polina Anikeeva (Materials Science and Engineering [DMSE]), Jessika Trancik (Engineering Systems Division), and Michael Watts (Electrical Engineering and Computer Science). In addition, professor Gang Chen (Mechanical Engineering), director of S^{3}TEC, reported on the center's activity.

Solid State Solar Thermal Energy Conversion Center

MPC completed its second year supporting the Solid State Solar Thermal Energy Conversion Center (S^{3}TEC), a US Department of Energy (DOE) Basic Energy Sciences–sponsored Energy Frontier Research Center. Led by Professor Chen, the center is a multidisciplinary effort that includes leading researchers from physics, chemistry, materials sciences, and electrical and mechanical engineering. The center's research focus has application in the use of solar and other heat sources in conversion to electrical energy.

Research is based on three major areas: (1) the study and control of photons for solar thermoelectric and thermophotovoltaics, (2) the understanding of electron and phonon transport, and (3) high-temperature reliability. The core activities of the center are focused on the investigation and development of thermoelectric materials, the collection and conversion of heat energy into electrical energy, and thermophotovoltaics for high-efficiency energy conversion of solar energy into electricity. Key to the energy conversion process is the ability to understand phonon transport processes in these materials, combined with the design and fabrication of highly selective surfaces to serve as efficient photon emitters in the case of thermophotovoltaic systems. Investigation of the material systems requires use of unique and adapted characterization tools, such as thermoreflectance, acoustic wave and phonon tomography (at Oak Ridge National Laboratory).

Based at MIT, MPC includes partnerships with Boston College and Oak Ridge National Laboratory and supports the research efforts of 12 principal investigators, multiple academic disciplines, and student and postdoctoral members assigned from their research teams. The center was officially launched in August 2009 for a five-year period, based on meeting annual reporting requirements. The goals of the research center would enable highly efficient harvesting of heat energy from multiple high-temperature processes, such as power plants, chemical plants, and engines (e.g., turbines and automobiles), in addition to realizing more efficient collection of the full solar energy spectrum into usable, sustainable green energy.

S^{3}TEC answered the call for submissions to DOE's Life at the Frontiers of Energy Research video contest. Selected by an external panel of judges, the video "Battle Against Phonons" was chosen as one of five winners and received the Special Award: Best with Popcorn prize. Judges included:

- Paula Apsell—senior executive producer, NOVA and NOVA ScienceNOW, and director, WGBH Science Unit
- William Phillips—fellow, National Institutes of Standards and Technology, and 1997 Nobel Prize winner in Physics
- Ivan Amato—senior communications officer, Pew Health Group, Pew Charitable Trusts, and author of *Stuff: The Materials the World Is Made Of* and *Super Vision: A New View of Nature*.

The official announcement of the award was posted on the Energy Frontier Research Center Summit and Forum website.

All the winning videos were shown during a plenary session at the Energy Frontier Research Center Summit and Forum, held May 25–27 in Washington, DC.

Microphotonics Center

MPhC is supported by a 15-member industry consortium whose members include Advanced Micro Devices, Alcatel-Lucent, Analog Devices, Advanced Photonic Integrated Circuits (APIC) Corporation, Corning, Electronics and Telecommunications Research Institute, Fujitsu, Hewlett Packard, International Business Machines, Intel Corporation, Kotura, LioniX, National Semiconductor, Nippon Electronics Corporation, Optitec, and Silicon on Insulator Technologies. MPhC features the Communication Technology Roadmap (CTR) program and its industry-led Technology Working Groups. The consortium is directed by MIT staff and one representative of each member company, forming the board of directors. Phase II of CTR was completed in 2009.

Organization of the roadmapping effort originated with the formation of three Technology Working Groups: (1) cross-market applications, (2) complementary metal-oxide-semiconductor platform; and (3) integration, packaging, and interconnect. Working group activities helped to support the funding of three CTR fellows, who worked closely with each working group, resulting in the authorship of white papers under the diligent direction of industry-based working group leaders. CTR III is now well underway, with a growing membership and a new structure for engagement and deliverable work products. Phase III working groups are currently focusing on baseline optical PCIe3.0+ and dimensions of scaling within an open architectures forum. Consortium members are working to form a consensus on identifying the parameters, needs, and distinctions between short-term and long-term links. Shifting from a four-year, 200-page document, CTR III will publish shorter, more frequent white papers on a revolving timeline to better match the industry cadence of a typical product cycle. Recent white paper titles include "Scaling Limits and Energy" and "The Limit of Copper Interconnect Scaling."

The Air Force Office of Scientific Research: Multidisciplinary University Research Initiative program in silicon lasers and nanophotonics completed the fifth and final year of research. The program, working in collaboration with seven other leading universities, has focused on the development of electrically pumped silicon-based lasers for silicon complementary metal-oxide-semiconductor chip-scale integration. The program resulted in the development of a germanium-based light source light-emitting diode, and promises the creation of an electrically pumped laser based on a group IV material that is compatible for integration both in size scale and materials processing compatibility, enabling ultra-low power, high-bandwidth signaling for on- and off-chip communications.

Selected New Programs with Industry

MPC continues to support faculty research efforts with industry collaboration over a wide range of materials science–based applications from metallurgical coatings for strength and corrosion resistance to integrated photonics, solar cells, and batteries. MPC supports many ongoing research programs with faculty, including professor Christopher Schuh's research with Mitsubishi Materials, professor Lionel Kimerling's program with Chanel, and a separate multicenter program that includes faculty from the Computer Science and Artificial Intelligence Laboratory and the Research Laboratory of Electronics on integrated photonics with APIC Corporation.

Promotions and Selected Honors and Awards

MPC faculty received numerous awards and honors, as individually reported in the reports of their home academic departments. Of special note are:

Pablo Jarillo-Herrero, along with Nuh Gedik (both assistant professors of physics) were among five from MIT to receive DOE early career research grants. Assistant Professor Jarillo-Herrero will use the funding to investigate novel quantum electronic transport phenomena in topological insulators. Assistant Professor Gedik received funding for a proposed project to develop short-pulse laser-based experimental tools to probe the ultra-fast electron dynamics of topological insulators—materials whose surface electrons have exceptional conducting properties distinct from the non-conductive nature of the bulk insulator material.

Professor Schuh, DMSE professor of metallurgy, was among the faculty named as MacVicar Fellows for their outstanding undergraduate teaching, mentoring, and educational innovation.

Michael Cima, DMSE professor of engineering, became a member of the National Academy of Engineering. Election to the academy is among the highest professional distinctions accorded to an engineer. Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature."

Two MPC research staff received important promotions this year: Anu Agarwal was promoted to principal research associate, and Jurgen Michel was promoted to senior research associate, the highest level in the research staff track.

Selected Faculty Highlights

Many MPC faculty have had significant accomplishments over the past year. Highlighted are two core MPC faculty and their research activities:

Eugene Fitzgerald, the Merton C. Flemings–SMA professor of materials engineering, coauthored the book *Inside Real Innovation*, which was published internationally in January. Professor Fitzgerald, who is also a visiting professor of management in the Johnson School at Cornell University, became interested in the innovation process through his experience in starting new companies based on technology developed within MPC. Building upon his early experience at AT&T Bell Laboratories, which included the invention of high-mobility strained silicon, he created fundamental innovations in stages, from early technology to final implementation in the market. Strained silicon is now used in most high-end integrated circuits manufactured worldwide. Basic work carried out at MIT was further developed as technology by Amberwave Systems, which was founded by Professor Fitzgerald in 1998.

Professor Fitzgerald subsequently founded or cofounded several other companies, including, most recently, 4Power LLC, which will commercialize high-efficiency solar cells composed of both III-V junctions and a silicon-germanium junction deposited on a silicon substrate. Eventually, the company hopes to reach the theoretical maximum of this optimally engineered solar cell, which is 50% AM1.5, and to do so at volume at the cost of silicon solar. In 2009, Professor Fitzgerald also cofounded Innovation Interface (initially funded by the Kauffman Foundation), a nonprofit organization that manages innovation projects between corporations and universities.

Amberwave Systems' and 4Power's basic technologies built on basic research on defects in semiconductors and heteroepitaxy conducted at MIT. This year, Professor Fitzgerald received the Institute of Electrical and Electronics Engineers 2011 Andrew S. Grove Award, which recognized his contribution to silicon-germanium lattice engineering on silicon for strained silicon and strained germanium devices. The award, one of the most prestigious offered by the association and only awarded 10 times in the past, recognizes outstanding contributions to solid-state devices and technology.

Donald R. Sadoway, the John F. Elliott professor of materials chemistry, has an expanding program focused on designing environmentally sound technologies for the extraction, refining, and recycling of metals, and developing rechargeable batteries for storage and delivery of off-peak power in stationary applications, as well as for automotive traction. With sponsorship from the American Iron and Steel Institute's CO_2 Breakthrough Program, a new process of the production of iron by electrolysis of molten iron oxide is underway. Enabled by the discovery of an industrially scalable new material that can serve as an oxygen-evolving anode, the process is totally carbon-free, energetically comparable to conventional steelmaking, and produces tonnage oxygen as a marketable by-product. The process chemistries have been devised for a variety of metals, and in laboratory-scale cells, the generation of iron, nickel, manganese, chromium, and titanium (each from its respective oxide) has been demonstrated. For each metal, the specific solvent electrolyte chemistry has been formulated and the instant electrochemistry of metal deposition and oxygen generation revealed. Next steps involve the construction and operation of a pre-pilot cell at the scale of 3000 Å, which will produce iron at the rate of ~50 kg per day.

Taking his inspiration from the economies of scale enjoyed by modern electrometallurgy, e.g., Hall-Héroult production of aluminum, Professor Sadoway has conceived of a new design of battery for grid-level storage. Termed the "liquid metal battery," the device consists of three liquid layers, continuously immiscible and stratified by density: on the top, a low-density alloy that serves as the negative electrode; on the bottom, a high-density alloy that serves as the positive electrode; and in between, a molten salt solution. On discharge, one of the constituents of the upper electrode ionizes and is transported to the lower electrode, where it discharges and alloys. Under sponsorship of the French energy company Total S.A. and DOE's ARPA–E, Professor Sadoway's team has explored the relevant fundamental chemistry and electrochemistry and demonstrated the reduction to practice of the liquid metal battery concept with a variety of alloys and salts. Laboratory cells of nominal 1 Ah capacity have been cycled for periods of weeks, exhibiting coulombic efficiencies in excess of 99%, energy efficiency greater than 90%, and fade rates of less than 0.07%, while meeting cost targets of less than $80/kWh and less than $150/kW for the electrode components. Scale-up has proceeded to 20 Ah cells, which have been operated for months without failure.

Promoting Exchange of Knowledge

As part of the MIT community, MPC's first priority is the education of the next generation of materials processing research scientists, engineers, and leaders. To this end, MPC initiates programs to enhance the intellectual vitality of the materials processing community.

Materials@MIT Gateway

MPC continues to expand its collaborations with other materials-related centers across campus to provide a common and guided gateway to the current maze of possibilities faced by outside visitors when approaching MIT with a materials interest. The Materials@MIT gateway web initiative (cosponsored by MPC, the Center for Materials Science and Engineering [CMSE], and DMSE) actively encourages the participation of all campus organizations involved in materials research.

The increasing shift to online information transfer has catalyzed a more focused initiative utilizing this site as a campus-wide materials reporting resource. Materials@MIT has become a highly successful portal for materials news and events within the MIT community. Faculties from several disciplines have availed themselves of the website's popularity, advertising well-received journal publications. The website has become a comprehensive repository of contact information for MIT start-up companies, MIT materials research centers, and

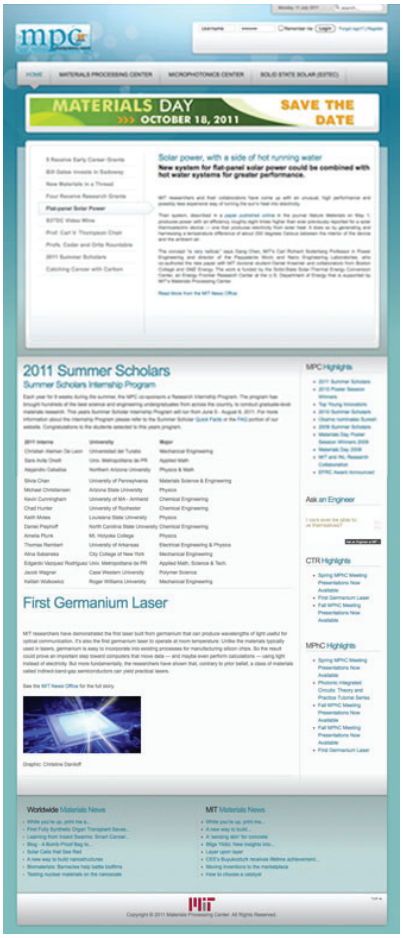


Figure 1: Screen capture of MPC website homepage featuring a news and announcements segment, a materials news articles segment, and worldwide and MIT materials news feeds

shared experimental user facilities. A comprehensive listing of academic programs, K–12 outreach programs, and campus-wide research reports is available at this site, in addition to a cross-departmental directory of faculty engaged in materials research.

Summer Research Internship Program

MPC does not limit its educational outreach to the MIT community. For 28 years, it has sponsored (now cosponsored with CMSE) a summer internship program for promising undergraduate researchers from other colleges and universities nationwide. The MPC summer internship (a nine-week program, which in 2011 runs from June 5 to August 6) is a National Science Foundation Research Experience for Undergraduates program that brings the best science and engineering undergraduates in the country to MIT for graduate-level materials research in laboratories of participating faculty. The program culminates in a poster session held in Lobby 13, where students present their research to the MIT community.

The 2010 program involved 14 faculty and 14 students from schools including Kenyon College, Cornell University, West Virginia University, University of Minnesota–Twin Cities, Universidad of del Turabo (Puerto Rico), and North Carolina State University.

More information about the MPC/CMSE Research Experience for Undergraduates summer internship in materials science can be found at http://mpc-web.mit.edu/.

Figure 2: 2010 summer scholars

Materials Day

Sharing knowledge and insight with others in the materials science and engineering field can lead to new ideas, collaborations, and breakthroughs. Once a year, the materials community is invited to Materials Day, a celebration to recognize and honor the many important accomplishments and achievements of the past year and to talk about the future.

Held in the fall in collaboration with CMSE, Materials Day is a daylong symposium on a featured topic, followed by a graduate student/postdoctoral associate poster session. The Materials Day 2010 symposium focused on materials for sensors and looked back at the 31-year legacy of MPC and how its widening focus has come to define an interdisciplinary hub of activity today. Seven presentations were made over the course of the day, from both faculty and industry professionals, drawing a standing-room-only crowd of more than 180 attendees.

Invited speakers and their talk titles included: professor Rajeev Ram, Electrical Engineering and Computer Science ("Sensors and Analytics for the Biopharmaceutical Industry"); Dr. Joyce Wong, Schlumberger–Doll Research Center ("Micro- and Nanoscale Sensors for Oil Reservoir Characterization"); professor Timothy Swager, Chemistry ("Carbon Nanotube-based Sensors"); professor Michael Strano, Department of Chemical Engineering ("Dancing on the Head of a Pin: The Coming Revolution in Nanosensors for Single Molecule Biodetection"); Dr. Tom Lowery, T2 Biosystems, ("Universal Platform for Decentralized, Rapid Clinical Diagnostics in Unprocessed Samples"); Professor Cima, DMSE ("Materials for Medical Diagnostic Sensors"); and professor Carl Thompson, DMSE and MPC director, who led the opening welcome presentation.

The poster session that followed panel presentations included over 84 posters presented by graduate students and postdoctoral associates from departments including Chemical Engineering, Chemistry, Civil and Environmental Engineering, Electrical Engineering and Computer Science, MIT Kavli Institute for Astrophysics and Space Research, DMSE, Mechanical Engineering, Nuclear Science and Engineering, and Physics. The posters were judged by a panel of representatives from industry as well as members from the MPC advisory board. Winners received award certificates and $500 prizes. Poster session winners were:

Explosives Detection with 9-, 10-Dithydroarldine Derivatives
Trisha L. Andrew, Chemistry
Advisor: Timothy Swager

Dual Functional Polyelectrolyte Multilayer Coatings for Implants: Permanent Microbicidal Base with Controlled Release of Therapeutic Agents
Sze Yinn Wong, Chemical Engineering
Advisor: Paula Hammond

Germanium Laser: A Bridge to the Photonic Network
Rodolfo Camacho-Aguilera, DMSE
Advisor: Lionel Kimerling

Resonant Cavity Enhancement of PbTe Films for IR Detectors on Si-ROICs
Timothy Zens, DMSE
Advisor: Lionel Kimerling

Materials Day 2011 is scheduled for October 18, 2011.

Figure 3: Materials Day 2010 Poster Session winners, from left to right: Rodolfo Camacho-Aguilera (DMSE); Sze Yinn Wong (Chemical Engineering); Timothy Zens (DMSE); Trisha L. Andrew (Chemical Engineering); Carl V. Thompson, director, MPC; and Dr. Ernest Littauer, advisory board member, MPC

International Partnerships with Industry and Government

MPC continues to collaborate with the Microsystems Technology Laboratories in managing the MIT–INL program. Research in four thrust areas was initiated this year:

- graphene-based microsystems for environment and food-quality monitoring
- nanomaterial arrays for integrated energy storage devices, supercapacitors, and sensors for autonomous sensor systems
- piezoelectric microelectromechanical systems for energy harvesting and actuation
- top-down templating of protein assembly: complex molecular self-assembly routes to biological device fabrication

Two of the four thrust areas are centered in MPC and two in the Microsystems Technology Laboratories. The first annual workshop for the MIT–INL program to be held in Braga, Portugal, will include presentations from MIT faculty already involved in the program, as well as INL collaborators and potential future participants. It is anticipated that this program, with a steady-state budget of $4M per year for five years, will eventually support about 10 research thrusts.

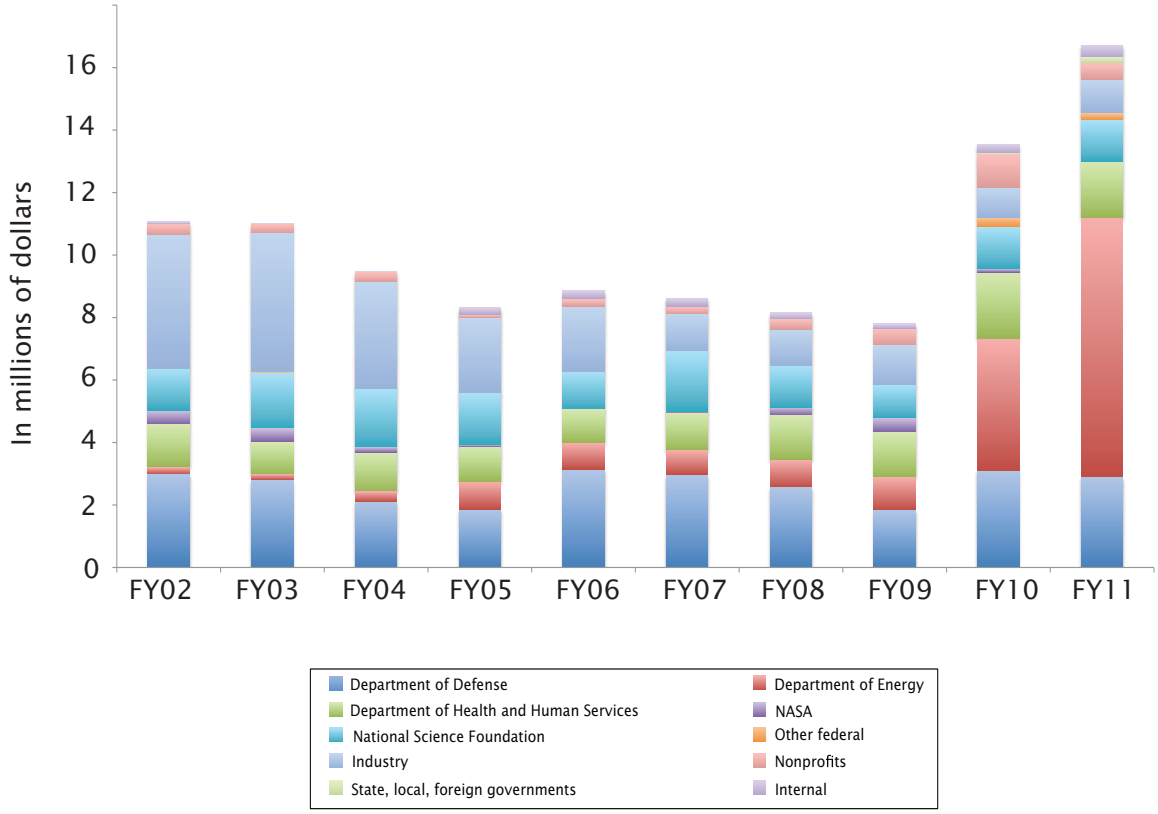
It was also recently announced that Professor Fitzgerald's proposed program on low-energy electronic systems will become the fifth and final research thrust in the Singapore–MIT Alliance for Research and Technology. This program will be run through MPC and will involve a number of the center's core faculty. The estimated budget will be $5M per year for five years; approximately 25% will be spent at MIT, and 75% at MIT's facility in Singapore.

Research Volume

MPC's five priority research areas are: medical materials, photonics, energy, environment, and nanotechnology. Total expenditures under MPC totaled over $18M in FY2011 (+20%). Major program expenditures included: Professor Sadoway's ARPA–E program on liquid metal batteries, Postdoctoral Associate Anna van Oudenaarden's National Institutes of Health (NIH) funding on stochastic gene expression and signal transduction in single cells, Professor Chen's S^{3}TEC DOE Energy Frontier Research Center work on solar-thermal energy, and Professor Kimerling's MPhC Multidisciplinary University Research Initiative and APIC program on silicon-based photonic integration. Campus materials research volume across MPC, CMSE, Institute for Soldier Nanotechnologies, and DMSE reached nearly $49.1M (+10.3%) for FY2011.

MPC researchers are sponsored not only by a variety of companies but also by nearly every major federal research–sponsoring agency, including the National Science Foundation, DOE, NIH, Defense Advanced Research Projects Agency, Air Force Office of Scientific Research, Office of Naval Research, and US Army Research Laboratory.

Figure 4: MPC sponsored research volume spanning FY2002–2011



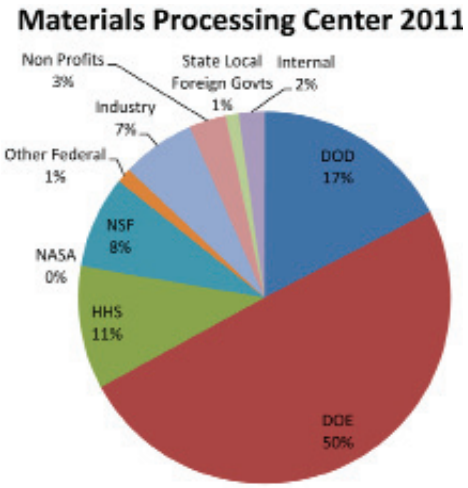


Figure 5: MPC major sponsors 2011

Outlook

In the coming year, MPC will help kick off the new Singapore–MIT Alliance for Research and Technology Centre program in low-energy electronic systems and will host the first MIT–INL workshop. The center will also continue to support S^{3}TEC and MPhC and many smaller research programs.

Because of MPC's expanding research portfolio and the new services to centers and programs that it provides, there is a need to expand from the current staff of four. MPC will recruit a senior financial officer and will likely recruit additional personnel in the area of communication. Staff growth will require an expansion of headquarters space, and MPC will seek access to a recently vacated adjacent office suite. An additional high priority for the center will be expansion of collegium membership and renewal of the industrial advisory board.

MPC looks forward to continuing its work with individual faculty and teams of faculty to develop and support new interdisciplinary research programs. As always, the center will continue to search for new ways to interact with industry in order to create collaborations that promote the two-way exchange of expertise and lead to the development of new materials and processes that provide a sustainable improvement in the quality of life worldwide.

Carl V. Thompson
Director
Professor of Materials Science and Engineering
Stavros Salapatas Professor of Materials Science and Engineering