Research Activity: Experimental Condensed Matter Physics

Division: Materials Sciences and Engineering
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Portfolio Description:

This program supports activities in experimental condensed matter physics that emphasize the relationship between electronic structure and the properties of complex systems whose behavior is often derived from electron correlation. Major efforts are in systems that exhibit correlated and emergent behavior with superconducting, semiconducting, magnetic, thermoelectric, and optical properties. These efforts are accompanied by activities to synthesize and characterize single crystals to further explore and discover new and novel correlated electron behavior. The program supports the development of new techniques and instruments for characterizing the properties of these materials under extreme conditions of ultra low temperature (mK) and ultra high magnetic fields (100 T). One main emphasis of this activity is on the electron dynamics of low dimensional systems. Confinement effects in high purity semiconductors produce new forms of matter and new physical phenomena such as the fractional Quantum Hall effect and Bose-Einstein Condensates. These low dimensional systems and other nanophase materials offer rich opportunities to explore their novel electronic behaviors.

Unique Aspects:

The research on magnetism and magnetic materials has more emphasis and direction than in other federally supported programs. It focuses on hard magnet materials, such as those used for permanent magnets and in motors, and on exchange biasing, such as used to stabilize the magnetic read heads of disk drives and the influence of nm length scales on magnetic materials properties. The Experimental Condensed Matter Physics (ECMP) activity continues to support research on electronically complex materials, an area that impacts a wide range of other topics including superconductivity, magnetoresistivity, low-dimensional electron systems, and magnetism including topics such as exchange bias and spin-polarized electron transport. The combined projects in superconductivity comprise a concerted and comprehensive energy-related basic research program. The Department of Energy (DOE) national laboratories anchor the efforts and maintain the integration with the Office of Electricity Delivery and Energy Reliability (OE) developmental efforts. Research on the properties of materials in high magnetic fields is being conducted using the 100 T multi-shot magnet at the Los Alamos National Laboratory (LANL). Two major areas of research are being pursued which include magnetic field induced phase transitions in addition to nano-quantization and quantum size effect. The ECMP activity also has unique thrusts in photoemission investigations of cuprate superconductors. It is a source of new materials scientists through strong programs at LANL, Sandia National Laboratories (SNL), Ames Laboratory, Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), and the Stanford Linear Accelerator Center (SLAC)**.** Internationally, the ECMP activity holds a position of world leadership in the areas of magnetism, superconductivity, materials characterization, and nanoscale science. New, exciting areas launched within this activity in photonic band gap materials, 2-D electron systems, magnetic superconductors, and quasicrystals are now pursued worldwide. Enhanced efforts are ongoing to generate high quality single crystals of new materials at Ames, ANL, BNL, Oak Ridge National Laboratory (ORNL), and SLAC.

Relationship to Other Programs:

This program and the National Science Foundation (NSF) support the National Academy of Science's Solid State Sciences Committee, which in turn serves as a coordinating mechanism nationally. The program has also supported topical activities at the National Academy of Sciences which included the *Decadal Assessment and Outlook for the Field of Condensed Matter and Materials Physics (CMMP) Research* and *An Assessment of New Materials Synthesis and Crystal Growth in the United States*. This research in the ECMP program is aimed at a fundamental understanding of the electronic behavior of materials that underpin DOE technologies. Improving the understanding of the physics of materials on the nanoscale will be technologically significant as these structures offer enhanced properties and could lead to dramatic improvements in energy generation, delivery, utilization, and conversion technologies. Specifically, research efforts in understanding the fundamental mechanisms in superconductivity, the elementary energy conversion steps in photovoltaics, and the energetics of hydrogen storage provide the major scientific underpinnings for the energy technologies. The granular materials research contributes to our understanding of radionuclide transport in groundwater and is of direct relevance to the environmental clean-up efforts. This activity also supports research of fundamental interest for information technology and electronics industries in the fields of semiconductor and spintronics research. These research efforts are closely coordinated with other core research activities in BES, including the Physical Behavior of Materials on photovoltaics, Synthesis and Processing Science on single crystal growth, X-ray and Neutron Scattering on photoemission studies, and Theoretical Condensed Matter Physics on nanostructures and low-dimensional systems. They are also coordinated with DOE technology programs in the Office of Energy Efficiency and Renewable Energy (EERE), OE, and Office of Environmental Management (EM).

Significant Accomplishments:

The ECMP activity has a long history of accomplishments dating back to the 1950s and the first neutron scattering experiments at ORNL. Notable accomplishments include the discovery of ion channeling and the development of the field of ion implantation; the discovery of metallic and strained-layer superlattices; the establishment of the field of thermoacoustics and thermoacoustic refrigeration and heating; the invention of Z-contrast scanning transmission electron microscopy; the theoretical and predictive basis for photonic band gap materials; the tandem photovoltaic cell; the observation of stripes in superconductors; the invention of a Josephson junction scanning tunneling microscope; the first observation of superconductivity in a magnetically doped semiconductor ($PtSb_2$ with ~1% Yb); the observation of Bose condensation of excitons doped double layer semiconductor structures; and the characterization of BCS and 2 Gap Superconductivity in magnesium diboride (MgB_2). In addition, the activity has supported much of the seminal work in the fields of high temperature superconductors and quasicrystals, efforts now pursued worldwide. The 100 T multishot magnet at Los Alamos was designed and constructed under the ECMP program and currently holds the world record for long pulse, high magnetic fields in a reusable magnet.

Mission Relevance:

This activity provides direct research assistance to the technology program in OE on superconductivity. This activity provides direct research assistance to the technology program in EERE on photovoltaics for solar energy conversion. In addition, it supports, more fundamentally, several DOE technologies and the strategically important information technology and electronics industries through its results in the fields of semiconductor physics and electronics research; the petroleum recovery efforts of the Office of Fossil Energy (FE) and the clean-up efforts of EM through research on granular materials and on fluids; and the R&D on advanced materials and magnets and thermoelectrics of EERE.

Scientific Challenges:

Among the immediate on-going scientific challenges are: the solution of the mechanism for high temperature superconductivity; the understanding of “stripes” in correlated electron systems; the understanding of novel quantum effects and of “emergent phenomena,” that is, new phenomena that emerge when the complexity of a system grows with the addition of more particles; the development of a very high-magnetic field research program to exploit the 100T and 60T magnets at LANL; research in nanoscale science; low-temperature physics; and the continued development of a materials synthesis and crystal growth capability in this country. Quality materials lie at the heart of quality measurements: a thrust to develop a core competence in the synthesis of new materials and the growth of crystals is underway, and it will continue to be a priority. High-magnetic-field research coupled with low temperature physics led to the discovery of the quantum Hall effect and to the general area of novel quantum effects. The availability of very high magnetic fields over useable time scales, as will be afforded by the new magnets at LANL, offers the promise of both increasing the fundamental understanding of matter and of observing the effects of very high magnetic fields on materials properties. This will undoubtedly lead to the discovery of new and exciting physics. Similarly, low temperature physics continues to be important for the advancement of physics by providing the experimental conditions necessary to observe phenomena such as BEC, the quantum Hall effect, and superconductivity. Developing and understanding matter and materials at the nano- and subnanoscale is a critical need because electronic, optical, and magnetic devices continue to shrink in size. Ballistic transport in quantum wires exceeding 5 μm in length may provide the basis for quantum computing.

Funding Summary:

Dollars in Thousands

FY 2007	FY 2008	FY 2009
42,720	40,720	50,509

Performer	Funding Percentage*
DOE Laboratories	70%
Universities	30%

*Based on FY2007
These are percentages of the operating research expenditures in this area; they do not contain laboratory capital equipment, infrastructure, or other non-operating components.

Projected Evolution:

The Experimental Condensed Matter Physics activity will include further work at the nanoscale; the development of a very high magnetic field research program; and continued development of the materials synthesis and crystal growth thrust. The portfolio can be expected to continue thrusts in electronic structure, new materials, surfaces/ interfaces, and experimental techniques. For example, sum frequency generation is a new technique that is now being used to probe the electronic and vibrational structure of chiral molecules on surfaces. Femtosecond time-resolved magnetooptical, terahertz, and x-ray diffraction techniques will be used to study the coupled dynamics of charge carriers along with the associated lattice deformations in high temperature superconductors, colossal magneto-resistance manganites, and charge density wave conductors. The subtopics also will be similar, e.g., magnetism, low dimensional electron systems, and new materials. Low temperature physics and superconductivity are important. Low temperature physics underlies several other areas of opportunity and presents issues of its own. Superconductivity, specifically high temperature superconductivity, continues to be a potentially revolutionizing technology. The goal for the former is to augment the investment in low temperature physics when possible. In superconductivity, the goal is to identify the most pressing scientific issues and ensure the level of effort is consistent with the priorities. New investigations in the Casimir force have been initiated. This attractive force between two surfaces in a vacuum, predicted over 50 years ago, could affect everything from micromachines to unified theories of nature.