Experimental Condensed Matter Physics

Portfolio Description

This activity supports Experimental Condensed Matter Physics) emphasizing the relationship between the electronic structure and the properties of complex materials, often at the nanoscale. The focus is on systems whose behavior derives from strong correlation effects of electrons as manifested in superconducting, semi-conducting, magnetic, thermoelectric, and optical properties. Also supported is the development of new techniques and instruments for characterizing the electronic states and properties of materials under extreme conditions, such as in ultra low temperatures (millikelvin), in ultra-high magnetic fields (100 Tesla), and at ultra-fast time scales (femtosecond). Capital equipment is provided for scanning tunneling microscopes, electron detectors, superconducting magnets, and physical property measurement instruments.

Unique Aspects

The Experimental Condensed Matter Physics 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. The research on magnetism and magnetic materials focuses on hard magnet materials, such as those used for permanent magnets and in motors; on exchange biasing, which is used to stabilize the magnetic read heads of disk drives; and on spin-polarized electron transport, particularly in nanometer-scale structures. The combined projects in superconductivity comprise a concerted and comprehensive energy-related basic research program. The 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 100T multi-shot magnet at the Los Alamos National Laboratory (LANL). Two major areas of research are being pursued: magnetic field induced phase transitions and nano-quantization and quantum size effect. The ECMP activity also has unique thrusts in photoemission investigations of superconductors and other correlated electron systems. It is a source of new materials scientists through strong materials synthesis programs at Oak Ridge National Laboratory (ORNL), Ames Laboratory, Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), SLAC National Accelerator Laboratory, LANL, and Sandia National Laboratories**.** Internationally, this 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, two-dimensional 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, ORNL, and SLAC.

Relationship to Other Programs

The research in the program is aimed at building a fundamental understanding of the electronic behavior of materials as a foundation for future energy technologies. Improving the understanding of the physics of materials at the nanoscale will be technologically significant as these structures offer enhanced properties and could lead to dramatic improvements in technologies for energy generation, conversion, delivery, and utilization. Specifically, research efforts aimed at understanding the fundamental mechanisms in superconductivity, the elementary energy conversion steps in photovoltaics, and the energetics of hydrogen storage provide scientific underpinnings for energy technologies. 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 and OE. This program and the National Science Foundation support the National Academy of Sciences' Condensed Matter and Materials Research Committee (formerly the Solid State Sciences Committee), which is charged with assessing the state of the field and advising federal agencies on research priorities. The program has also supported topical studies by the National Research Council, including *CMMP 2010: An Assessment of and Outlook for Condensed-Matter and Materials Physics* and *Assessment of and Outlook for New Materials Synthesis and Crystal Growth*.

Significant Accomplishments

This 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 two-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 LANL was designed and constructed under this program and currently holds the world record for long pulse, high magnetic fields in a reusable magnet.

Mission Relevance

Improving the understanding of the electronic behavior of materials on the atomistic scale is relevant to the DOE mission, as these structures offer enhanced properties and could lead to dramatic improvements in technologies for energy generation, conversion, storage, delivery, and use. Specifically, research efforts in understanding the fundamental mechanisms of superconductivity, the elementary energy conversion steps in photovoltaics, and the energetics of hydrogen storage provide the major scientific underpinnings for the respective energy technologies. This activity also supports basic research in semiconductor and spin-based electronics of interest for the next generation information technology and electronics industries.

Scientific Challenges

Among the immediate on-going scientific challenges faced by this program are the following: 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 is now afforded by the new magnet 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 nanoscale is a critical need because electronic, optical, and magnetic devices continue to shrink in size.

Projected Evolution

The Experimental Condensed Matter Physics activity will include further work at the nanoscale and at low temperatures, 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 development of experimental techniques. Efforts will continue to strengthen research in unconventional superconductivity, including the high-temperature cuprate superconductors, first discovered nearly 25 years ago, and the recently discovered iron pnictide superconductors. In the last few years the program has increased support for spin physics and nanomagnetism, and new investigations of the Casimir force have been initiated. Recently the program has begun to explore whether cold atom research can provide insight into open questions about correlated electron behavior in condensed matter systems.