Condensed-Matter and Materials Physics

Basic Research for Tomorrow's Technology

Committee on Condensed-Matter and Materials Physics
Board on Physics and Astronomy

Commission on Physical Sciences, Mathematics, and Applications

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Front cover: A scanning-tunneling microscope image that shows the wave nature of electrons confined in a "quantum corral" of 48 individually positioned atoms. See page 233. (Courtesy of IBM Research.)

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Preface

In the spring of 1996, the National Research Council's Board on Physics and Astronomy established the Committee on Condensed-Matter and Materials Physics to prepare a scholarly assessment of the field as part of the new survey of physics, *Physics in a New Era,* that is now in progress. This assessment has five objectives.

1. Identify future opportunities and priorities in the field.
2. Articulate the fundamental scientific challenges in the field.
3. Assess related infrastructure, institutional, resource, and educational issues.
4. Provide evidence of the societal impact of the field.
5. Provide a forum for coordinated community-wide communications with federal agencies, policy makers, and the public.

The committee was composed of individuals whose backgrounds reflect the diversity of the field and its close connections with related branches of science, including chemistry, biology, and engineering. The field spans research environments from principal investigators carrying out benchtop studies in universities to large collaborations carrying out experiments at major national facilities. It also spans the forefronts of many-body theory, the behavior of complex materials and fluids, and the design of semiconductor devices and circuits. Condensed-matter and materials physics research is carried out in various institutional settings, including university, government, and industrial research laboratories.

In the course of the study, the committee held two workshops on research frontiers and policy issues. These workshops brought together leading researchers in the field as well as leading policy makers from government, industry, and universities. The committee met several times to plan its work, debate the issues, and formulate its report. An early output of the study was the report *The Physics of Materials: How Science Improves Our Lives*, a short, colorful, and easy-to-read pamphlet illustrating how research in the field affects our daily lives. The committee generated several progress reports and held public forums at materials-related meetings of the American Physical Society and the Materials Research Society. The committee also sought input from the general science and engineering communities. We are particularly grateful to our colleagues in biology, chemistry, and materials and electrical engineering for their support and help in carrying out this study.

The committee would like to thank Donald C. Shapero, Daniel F. Morgan, and Kevin D. Aylesworth from the Board on Physics and Astronomy for their efforts throughout the course of this study. Special thanks also to Arthur Bienenstock, who served on the committee until the fall of 1997, when he assumed responsibilities at the Office of Science and Technology Policy. The committee gratefully acknowledges the contributions of the following individuals who provided material or particular advice that influenced its study: David Abraham, Eric J. Amis, Bill Appleton, Meigan Aronson, David Aspnes, John Axe, Arthur P. Baddorf, Samuel Bader, A. Balazs, N. Balsara, Troy Barbee, F. Bates, Bertram Batlogg, Robert Behringer, Jerzy Bernholc, Arthur Bienenstock, Jörg Bilgram, Howard Birnbaum, Stephen G. Bishop, Steve Block, Lynn A. Boatner, Eberhardt Bodenschatz, Greg Boebinger, William Boettinger, Bill Brinkman, R. Bubeck, David Cannell, Federico Capasso, G. Slade Cargill, John Carruthers, Robert Cava, Robert Celotta, David Ceperley, Paul Chaikin, Albert Chang, S.S. (Leroy) Chang, Eric Chason, Daniel Chemla, Shiyi Chen, S. Cheng, B. Chmelka, Alfred Cho, John R. Clem, Daniel Colbert, Piers Coleman, George Crabtree, George Craford, Harold Craighead, Roman Czujko, Elbio Dagatto, Adriaan de Graaf, Satyen Deb, Patricia Dehmer, Cees Dekker, David DiVincenzo, Russ Donnelly, Robert Doremus, J. Douglas, Mildred S. Dresselhaus, Bob Dunlap, J. Dutcher, Bob Dynes, Robert Eisenstein, Chang-Beom Eom, Evan Evans, Ferydoon Family, Matthew P.A. Fisher, Zachary Fisk, Paul Fleury, Mike Fluss, Judy Franz, Jean Fréchet, Glenn Fredrickson, Hellmut Fritsche, William Gallagher, E. Giannelis, Allen M. Goldman, Jerry Gollub, Matt Grayson, P. Green, G. Grest, Peter Grüter, Richard Hake, Thomas Halsey, Donald Hamann, Christopher Hanna, Bill Harris, Beverly Hartline, Kristl Hathaway, Lance Haworth, Frances Hellman, George Hentschel, Jan Herbst, Pierre Hohenberg, Susan Houde-Walter, Evelyn Hu, Robert Hull, David Huse, Eric Isaacs, Nikos Jaeger, Adam B. Jaffe, Sungho Jin, David Johnson, James Jorgensen, Malvin H. Kalos, A. Karin, Marc Kastner, Efthimios Kaxiras, Jeffrey Koberstein, Carl C. Koch, Kei Koizumi, J. Kornfield, Mark Kryder, Max Lagally, David V. Lang, Robert Laudise, G. Leal, Manfred Leiser, Ross Lemons, Joseph Levitzky, Peter Levy, David Litster, T. Lodge, Gabrielle Long, Steven Louie, Michael

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The committee's work was supported by grants from the U.S. Department of Commerce, the U.S. Department of Energy, and the National Science Foundation. The committee thanks them for their support.

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The contents of the review comments and the draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Phillip W. Anderson, Princeton University,
Steven Chu, Stanford University,
Esther Conwell, University of Rochester,
Robert Dynes, University of California, San Diego,
Val Fitch, Princeton University,
Paul Fleury, University of New Mexico,
Jerry P. Gollub, Haverford College,
David Moncton, Argonne National Laboratory,
Thomas Russell, University of Massachusetts, Amherst, and
Thomas Theis, IBM T.J. Watson Research Center.

Although the individuals listed above have provided many constructive comments and suggestions, the responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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Condensed-Matter and Materials Physics

Executive Summary

Condensed-matter and materials physics plays a central role in many of the scientific and technological advances that have changed our lives so dramatically in the last 50 years. Condensed-matter and materials physics gave birth to the transistor, the integrated circuit, the laser, and low-loss optical fibers so important to the modern computer and communications industries. The years ahead promise equally dramatic advances, making this an era of great scientific excitement for research in the field. Communicating this excitement and ensuring further progress are the main goals of this report.

In the decade since the last major assessment of the field, important results and discoveries have come rapidly and from unexpected directions. These results and discoveries have made possible advances that range from new experimental tools for atomic-scale manipulation and visualization, to the creation of new synthetic materials (such as buckyballs and high-temperature superconductors), to new physical phenomena such as giant magnetoresistance and the fractional quantum Hall effect. An enormous increase in computing power has yielded qualitative changes in visualization and simulation of complex phenomena in large-scale many-atom systems. Progress in synthesis, visualization, manipulation, and computation will continue to have an impact on many areas of research spanning different length scales from atomic to macroscopic. Strong impact may also be expected in "soft" condensed-matter physics, particularly where it interfaces with biology and chemistry.

The priorities of society are shifting from military security to economic well-being and health. Changing societal priorities, in turn, create shifting demands on condensed-matter and materials physics. Among these demands are an improved public understanding of science, better education of scientists and engineers for today's employment marketplace, and new contributions to the nation's industrial competitiveness.

There are four key challenges facing condensed-matter and materials physics:

- The intellectual vitality of the field must be nurtured, particularly by facilitating the research of individual investigators and small teams in areas that cross disciplinary boundaries.
- A state-of-the-art facilities infrastructure is essential for competitive research; such an infrastructure requires the creation of laboratory-scale microcharacterization facilities at universities and large-scale facilities at national laboratories.
- Efforts must be enhanced in research universities to improve integration of condensed-matter and materials physics education and research, particularly at the boundaries of disciplines, and to prepare flexible and adaptable physicists for the future.
- New modes of cooperation among universities, colleges, government laboratories, and industry need to be developed that will ensure the connection between the field and the needs of society and to ensure preservation of the fertile innovative climate of major industrial laboratories that have played a dominant role in condensed-matter and materials physics research.

In this report the committee makes a number of recommendations for steps to be taken to meet these challenges. They are outlined here and discussed more extensively in the Overview and in further detail in each of the chapters.

For the overall research effort to address the full range of problems facing the field, a hierarchy of approaches is necessary. The core of the research effort in condensed-matter and materials physics is in the work of individual investigators and small research groups. Some of the most innovative and creative developments originate in this mode of research. At the next levels, larger groups, centers, and entire laboratories cooperate on significant problems, aided by progressively more-complex instrumentation and facilities. Theoretical work and benchtop experiments are usually done by individual investigators. Small-scale centers located in universities and government laboratories play an essential role in a number of areas including microcharacterization, processing, synthesis, and state-of-the-art instrumentation development. The highest level in the hierarchy is exemplified by major facilities, including synchrotron light sources, centers for neutron-scattering research, and laboratories for high magnetic field studies. These major facilities address a broad range of problems. An area of particularly rapid growth is found in the use of these major facilities, particularly synchrotron light sources, in understanding soft condensed matter and biological systems. A key facilities problem is the critical gap in U.S. capabilities in the area of neutron sources.

The different modes of research—benchtop experiments, larger collaborations, and so on—are evolving steadily. The work carried out in these varied modes is complex and diverse and continuously expanding to encompass an increasing number of disciplines. The committee has paid special attention to describing the forefronts of condensed-matter and materials physics research in conjunction with a small number of research themes. These themes are discussed in some detail in the Overview and reappear in each of the chapters. Throughout this study the themes of new experimental and computational capabilities, the ability to address problems of increasing complexity, and the importance of relationships with other fields are interwoven with discussion of subdisciplines of condensed-matter and materials physics. One of the subdisciplines that has captured the imagination of theorists and experimenters alike is the structure and properties of materials at reduced dimensionality—for example, in planar structures. Developing large-scale integrated circuits depends on understanding the behavior of semiconductors in such configurations, so the potential for impact is apparent.

A number of actions are required to maintain and enhance productivity in the field of condensed-matter and materials physics. These actions involve each level of the hierarchy of research modalities *and the interactions among the various levels and the various performers*. The principal recommendations of the committee are summarized here:

- The National Science Foundation, the U.S. Department of Energy, the U.S. Department of Defense, and other agencies that support condensed-matter and materials physics research should continue to nurture the core research at the heart of the field. The research areas described in the Overview provide a guide to the scientific arenas at the forefront of this work.
- The agencies that support and direct research should plan for increased investment in modernizing the condensed-matter and materials physics research infrastructure at universities and government laboratories.
- The National Science Foundation should increase its investment in state-of-the-art instrumentation and fabrication capabilities, including centers for instrumentation R&D, nanofabrication, and materials synthesis and processing at universities. The Department of Energy should strengthen its support for such programs at national laboratories and universities.
- The insufficiency of neutron sources in the United States should be addressed in the short term by upgrading existing neutron-scattering facilities and in the long term by the construction of the Spallation Neutron Source.
- Support for operations and upgrades at synchrotron facilities, including research and development on fourth-generation light sources, should be strengthened.
- The broad use of synchrotron and neutron facilities across scientific disciplines and sectors should be considered when establishing agency budgets.

- Federal agencies should provide incentives for formation of partnerships among universities and government and industrial laboratories that carry out research in condensed-matter and materials physics.
- Universities should endeavor to enhance their students' understanding of the role of knowledge integration and transfer as well as knowledge creation.