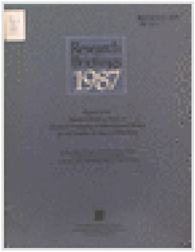

Research Briefings 1987: Report of the Research Briefing Panel on Chemical Processing of Materials and Devices for Information Storage and Handling (1987)

Pages
21

Size
8.5 x 11

ISBN
0309320755

Committee on Science, Engineering, and Public Policy; National Academy of Sciences; National Academy of Engineering; Institute of Medicine

Research Briefings 1987

Report of the Research Briefing Panel on Chemical Processing of Materials and Devices for Information Storage and Handling

for the Office of Science and Technology Policy,
the National Science Foundation,
and Selected Federal Departments and Agencies

Committee on Science, Engineering, and Public Policy (U.S.). Research Briefing Panel on Chemical Processing of Materials and Devices for Information Storage and Handling.
National Academy of Sciences
National Academy of Engineering
Institute of Medicine

NATIONAL ACADEMY PRESS
Washington, D.C. 1987

National Academy Press 2101 Constitution Avenue, NW Washington, DC 20418

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This work was supported by the National Science Foundation.

Printed in the United States of America

Research Briefing Panel on Chemical Processing of Materials and Devices for Information Storage and Handling

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*The reports listed here are published in *Research Briefings 1987, Research Briefings 1986*, etc., by the National Academy Press, Washington, D.C.

Preface

Research Briefings 1987 is the sixth volume of research briefing reports published by the Committee on Science, Engineering, and Public Policy (COSEPUP).* It brings to 37 the number of such reports prepared on a broad range of topics since the first volume in 1982 (see the list of topics on page iv). The briefings are prepared at the request of the President's Science Advisor, who also serves as Director of the Office of Science and Technology Policy (OSTP), and the Director of the National Science Foundation (NSF).

Five reports are presented in this collection—the first four on what might be called traditional science and technology topics similar to those covered in earlier years, and the fifth on a policy topic, which is a new departure for the research briefing activity. The policy briefing was undertaken at the specific request of Erich Bloch, Director of the NSF, who encouraged COSEPUP to apply the research briefing approach to a broader set of issues. One of the four traditional briefings (High-Temperature Superconductivity) was also prepared at the specific request of the NSF director after the 1987 briefing activity was already well under way, in response to the exciting new developments in superconductivity in ceramic oxide materials announced earlier this year.

Research briefing topics generally are selected by the OSTP and NSF directors in the late fall in response to suggestions put forward by COSEPUP. COSEPUP's suggestions are selected from a much larger list of suggestions offered by the commissions and boards of the National Research Council (NRC); members of the NAS, NAE, and IOM Councils; members of COSEPUP; as well as officials of the NSF and OSTP. Individual briefings are designed either (1) to assess the status of a field and identify high-leverage research opportunities and barriers to progress in the field (including where appropriate, progress in commercial exploitation), or (2) to identify and illuminate critical aspects of a policy issue related to the health of U.S. science and technology. The briefings are then prepared by panels of experts, usually in the spring, with the day-to-day assistance of NRC staff. This schedule allows time for COSEPUP review in late spring and

*COSEPUP is a joint committee of the National Academy of Sciences (NAS), the National Academy of Engineering (NAE), and the Institute of Medicine (IOM).

Report of the Research Briefing Panel on Chemical Processing of Materials and Devices for Information Storage and Handling

INTRODUCTION

Almost every aspect of our lives—at work, at home, and in recreation—has been affected by the information revolution. Today, information is collected, processed, displayed, stored, retrieved, and transmitted through the use of an array of powerful technologies that rely on electronic microcircuits, lightwave communication systems, magnetic and optical data storage and recording, and electrical interconnections. Materials and devices for these technologies are manufactured using sophisticated chemical processes. The United States is now engaged in a fierce international competition to achieve and maintain supremacy in the design and manufacture of materials and devices for information storage and processing. The economic stakes are large (see Table 1); national productivity and security interests dictate that we make the strongest possible efforts to stay ahead in processing science and technology for this area.

This briefing explores the chemical processing required in three of these key technologies: electronic microcircuits, lightwave communication systems, and magnetic recording media. This briefing also explores briefly some potential needs for advanced chemical processing that may be required to realize more fully the promise of superconducting metal oxides.

In high-technology manufacturing of components for information systems, there has been a long-term trend away from mechanical production and toward production using chemical processes. In several of these industries, chemists and chemical engineers have become increasingly involved in research and process development. Worldwide, though, many high-technology industries, such as the microelectronics industry, still have surprisingly little strength in chemical processing and engineering. The United States has a special advantage over its international competitors—its chemical engineering research community leads the world in size and sophistication. The United States is in a position to exploit its strong competence in chemical processing to (1) regain leadership in areas in which the initiative in manufacturing technology has passed to Japan, and (2) maintain or increase leadership in areas of U.S. technological strength.

To achieve their potential contribution fully, it is of paramount importance that chemical engineers strongly interact with

TABLE 1 Total Estimated Worldwide Market for Materials and Devices for Information Storage and Handling (billions of 1986 dollars)

	Year		
Technology	1985	1990	1995
Electronic semiconductors	25	60	160
Lightwaves	1	3	5.5
Recording materials	7	20	55
Interconnections	10	21	58
Photovoltaics	0.3	0.8	3
Total Electronics	397	550	(n.a)

Source: AT&T Bell Laboratories.
Compiled from various published sources.

other disciplines in high-technology industries and have the ability to communicate across disciplinary lines. The technologies discussed in this report cross over disciplines such as solid-state physics and chemistry, surface and interfacial science, electrical engineering, and materials science.

Materials and devices for information storage and handling are exceedingly diverse, yet they have many characteristics in common: the products are high in value; they require relatively small amounts of energy or materials to manufacture; they have short commercial life cycles; and their markets are fiercely competitive—consequently, these products experience rapid price erosion. The manufacturing methods used to produce integrated circuits, optical fiber, and recording media also have common characteristics. Each of these products is manufactured using a sequence of individual, complex steps, most of which entail the chemical modification or synthesis of materials. The individual processes are designed as discrete unit or batch operations and, to date, there has been little effort to integrate the overall manufacturing process. Because chemical reactions and processes are used in the manufacture of this broad array of materials and devices, chemical engineers could play a significant role in improving manufacturing processes and techniques, and investments in chemical processing science and engineering research represent a potentially high-leverage approach to improving our competitive position.

CURRENT CHEMICAL MANUFACTURING PROCESSES

Microcircuits

The use of chemical reactions and processes in the manufacture of microcircuits begins with the basic material for integrated circuits, high-purity (less than 150 parts per trillion of impurities) polycrystalline silicon. This ultrapure silicon is produced from metallurgical grade (98 percent pure) silicon, by (1) reaction at high temperature with hydrogen chloride to form a complex mixture containing trichlorosilane; (2) separation and purification of trichlorosilane by absorption and distillation; and (3) reduction of ultrapure trichlorosilane to polycrystalline silicon by reaction with hydrogen at 1100–1200°C. To prepare single-crystal silicon ingots suitable for use as materials in semiconductors, polycrystalline silicon is melted in a crucible at 1400–1500°C under an argon atmosphere. Tiny quantities of dopants—compounds of phosphorus, arsenic, or boron—are then added to the melt to achieve the desired electrical properties of the finished single-crystal wafers. A tiny seed crystal of silicon with the proper crystalline orientation is inserted into the melt and slowly rotated and withdrawn at a precisely controlled rate, forming a large (15 cm × 1.8 m) cylindrical single crystal with the desired crystalline orientation and composition. Crystal growth kinetics, heat and mass transfer relationships, and chemical reactions all play important roles in this process of controlled growth. The resulting single-crystal ingots are sawed into wafers that are polished to a flatness in the range of from 1 to 10 μm.

The next steps in device fabrication are the sequential deposition and patterning of thin dielectric and conducting films. The polished silicon wafer is first oxidized in a furnace at 1000–1200°C. The resultant silicon dioxide film is a few hundred nanometers thick and extremely uniform. The wafer is then coated with an organic photosensitive material, termed a resist, and is exposed to light through the appropriate photomask. The purpose of the photolithographic process is to transfer the mask pattern to the thin film on the wafer surface. The exposed organic film is developed with a solvent that removes unwanted portions, and the resulting pattern serves as a mask for chemically etching the pattern into the silicon dioxide film. The resist is then removed with an oxidizing agent such as a sulfuric acid-hydrogen peroxide mixture, then the wafer is chemically cleaned and is ready for other steps in the fabrication process.

The patterned wafer might next be placed in a diffusion furnace, where a first doping step is performed to deposit phosphorus or boron into the holes in the oxide. A new oxide film can then be grown and the photoresist process repeated. As many as 12 layers of conductor, semiconductor, and dielectric materials are deposited, etched, and/or doped to build the three-dimensional structure of the microcircuit. Thus a semiconductor device is a series of electrically interconnected films, the successful growth and manipulation of which depends heavily on proper reactor design, the choice of chemical reagents, separation and purification steps, and the design and operation of sophisticated control systems.

Lightwave Media and Devices

Optical fibers are also made by chemical processes. The critical feature of an optical fiber that allows it to propagate light down its length is a core of high refractive index surrounded by a cladding of lower index. The higher index core is produced by doping silica with oxides of phosphorus, germanium, and/or aluminum. The cladding is either pure silica or silica doped with fluorides or boron oxide.

Four processes are principally used to manufacture the glass body that is drawn into today's optical fiber. "Outside" processes, such as outside vapor-phase oxidation and vertical axial deposition, produce layered deposits of doped silica by varying the concentration of $SiCl_4$ and dopants passing through a torch. The resulting "soot" of doped silica is deposited and partially sintered to form a porous silica boule. In a second step, the boule is sintered to a pore-free glass rod of exquisite purity and transparency. "Inside" processes, such as modified chemical vapor deposition (MCVD) and plasma chemical vapor deposition (PCVD), deposit doped silica on the interior surface of a fused silica tube. In MCVD, the oxidation of the halide reactants is initiated by a flame that heats the outside of the tube. In PCVD, the reaction is initiated by a microwave plasma. Over a hundred different layers with different refractive indexes (a function of glass composition) may be deposited by either process before the tube is collapsed to form a glass rod.

In current manufacturing plants for glass fiber, the glass rods formed by all of the abovementioned processes are then carried to another facility where they are drawn into a thin fiber and immediately coated with a polymer. The polymer coating is important; it protects the fiber surface from microscopic scratches, which can seriously degrade the glass fiber's strength.

Current manufacturing technologies for optical fiber are relatively expensive, compared to the low cost of commodity glass. U.S. economic competitiveness in optical technologies would be greatly enhanced if low-cost means were found for producing waveguide-quality silica glass. The manufacture of glass lends itself to a fully integrated and automated process (i.e., a continuous process). One can envision a fiber manufacturing plant that starts with the purification of chemical reagents, which is then followed by a series of chemical reactions, glass-forming operations, and finally fiber-drawing steps. In such a plant, intermediate products would never be removed from the "production line." Sol–gel and related processes are attractive candidates for such a manufacturing process, which would start with inexpensive ingredients and proceed from a sol to a gel, to a porous silica body, to a dried and sintered glass rod, and finally to drawn and coated fibers. Such a process could reduce the cost of glass fiber by as much as a factor of 10, a step that would greatly increase the scope, availability, and competitiveness of lightwave technologies.

At present the chemical steps involved in sol–gel processes are poorly understood. Methods are being sought to manipulate these processes to produce precisely layered structures in a reliable and reproducible way.

Recording Media

Recording media come in a variety of formats (e.g., magnetic tape, magnetic disks, or optical disks) and are made using a variety of materials and processes (e.g., evaporated thin films or deposited magnetic particles in polymer matrixes). To illustrate the chemical reactions and processes in the manufacture of recording media, this section focuses on magnetic particle technology, an economically important part of the market for which the processing challenges are easy to discuss. Chemical reactions and processes are equally relevant to emerging technologies and materials in recording.

The manufacture of magnetic recording media depends heavily on chemical processing. The density at which information can be recorded is determined by the chemical and physical properties of the magnetic particles or thin films coated on a disk or tape. Paramount among these properties are the shape, size, and size distribution of the magnetic particles. An extremely narrow range in the size of magnetic particles—themselves only a few tenths of a micron in size—must be achieved in a reliable and economic manner. These particles must be deposited in a highly oriented fashion, so that high recording densities can be achieved by having the magnetic particles lie as closely together as possible. Accomplishing this requires the solution of a variety of challenging problems in the chemistry and chemical engineering of barium ferrite and the oxides of chromium, cobalt, and iron (e.g., the synthesis and processing of micron-sized materials with specific geometric shapes).

The manufacture of magnetic tape illustrates an interesting sequence of chemical processing challenges. A carefully prepared dispersion of needle-like magnetic particles is coated onto a fast-moving (150–300 m/min) polyester film base that is 0.0066- to 0.08-mm thick. The ability to coat thin, smooth layers of uniform thickness is crucial. The coated particles are oriented in a desired direction either magnetically or mechanically during the coating process. After drying, the tape is calendared—squeezed between microsmooth steel and polymer rolls that rotate at different rates, providing a "microslip" action that polishes the tape surface. These manufacturing steps (i.e., materials synthesis, preparation and handling of uniform dispersions, coating, drying, and calendaring) are chemical processes and/or unit operations that are familiar territory to chemical engineering analysis and design.

INTERNATIONAL COMPETITIVE ASSESSMENT

Introduction

In each of the technologies described in the preceding section, U.S. leadership in both fundamental research and manufacturing is severely challenged, and in some cases the United States has been judged to lag behind foreign competitors such as Japan.

MICROCIRCUITS

A recent report of the National Research Council* has assessed the comparative position of the United States and Japan in advanced processing of electronic materials. The report, which focuses heavily on evaluating Japanese research on specific process steps in the manufacture of electronic materials, provides significant background for the following observations.

- The U.S. electronics industry appears to be ahead of, or on a par with, Japanese industry in most areas of current techniques for the deposition and processing of thin films—chemical vapor deposition (CVD), metalorganic chemical vapor deposition (MOCVD), and molecular beam epitaxy (MBE). There are differences in some areas, though, that may be crucial to future technologies. For example, the Japanese effort in low-pressure microwave plasma research is impressive and surpasses the U.S. effort in some respects. The Japanese are ahead of their U.S. counterparts in the design and manufacture of deposition equipment, as well.
- Japanese industry has a very substantial commitment to advancing high-resolution lithography at the fastest possible pace. Two Japanese companies, Nikon and Canon, have made significant inroads at the cutting edge of optical lithography equipment. In the fields of x-ray and electron-beam lithography, it appears that U.S. equipment manufacturers have lost the initiative to Japan for the development of commercial equipment.
- Japanese researchers are ahead of their U.S. counterparts in the application of laser and electron beams and solid-phase epitaxy for the fabrication of silicon-on-insulator structures.
- The United States leads in basic research related to implantation processes and in the development of equipment for conventional applications of ion implantation. Japan appears to have the initiative in the development of equipment for ion microbeam technologies.

Neither the United States nor Japan has satisfactorily solved the problems of process integration in microcircuit manufacture. As the previous comparisons indicate, much effort is being expended on equipment design for specific processing steps, but a parallel effort to integrate the processing of these materials across the many individual steps has received less attention in both countries. Yet the latter effort might have significant payoffs in improved process reliability and efficiency—that is, in "manufacturability." The United States has the capability to take a significant lead in this area.

LIGHTWAVE TECHNOLOGY

The Japanese are our prime competitors in the development of lightwave technology. They are not dominant in the manufacture of optical fiber thanks in part to a strong overlay of patents on basic manufacturing processes by U.S. companies. In fact, a major Japanese company manufactures optical fiber in North Carolina for shipment to Japan. This is the only example to date of Japan importing a high-technology product from a U.S. subsidiary. Nonetheless, the Japanese are making strong efforts to surpass the United States, and are reaching a par with the United States in many areas.

The United States still significantly leads Japan in producing special purpose and high-strength fibers, in preparing cables from groups of fibers, and in research on hermetic coatings for fibers.

RECORDING MEDIA

Japan is the United States' principal technological competitor in the manufacture of

* Panel on Materials Science, National Materials Advisory Board. Advanced Processing of Electronic Materials in the United States and Japan. Washington, D.C.: National Academy Press, 1986.

magnetic media, and Korean firms are beginning to make significant inroads at the low end of the market for magnetic tape. U.S. companies producing magnetic tape use manufacturing processes that achieve higher integration through combined unit operations, but Japanese companies have a higher degree of automation in these separate operations. U.S. companies are ahead of the Japanese in the use of newer thermoplastics in calendar-compliant roll materials. Japan used to surpass the United States in the product uniformity of magnetic tape for professional applications; U.S. firms have closed this gap in recent years, and are now capturing worldwide market share from the Japanese, even in Japan.

The most significant development in Japan is the entry of photographic film companies (i.e., Fuji and Konishuroku) into the manufacture of magnetic media. They are having a large impact because the heart of the manufacturing process is the deposition of thin layers, and chemical processing technology from the photographic film business can be used to improve the quality and yield of magnetic tape.

The United States still lags behind Japan in the treatment and manufacture of magnetic particles (except possibly for 3M, which manufactures its particles internally). There are disturbing signs that the Japanese may be ahead of the United States in the next generation of film base, especially the film base for vapor-deposition magnetic media. The situation is not entirely clear, because 3M and Kodak make their own proprietary film. Other U.S. magnetic media companies, though, may be buying their film technology from Japan in the future.

General Observations

As noted previously, the industries that manufacture high-technology materials and components for information processing and storage are characterized by short product life cycles, enormous competition, and rapid erosion of product value. These industries also need rapid technology transfer from the research laboratory onto the production line. Many of their *products* cannot be protected by patents, except for minor features. The key to their competitive success is thoroughly characterized and integrated manufacturing *processes*, supported by process innovations. In the past, much of the process technology on which these industries depend has been developed empirically. If the United States is to maintain a competitive position in these industries, it is essential that we develop the fundamental knowledge necessary to stimulate further improvement of, and innovation in, processes involving chemical reactions that must be precisely controlled in a manufacturing environment. In the next section the principal technical challenges are set forth.

GENERIC RESEARCH ISSUES

Introduction

A variety of important research issues are ripe for a substantially increased effort to enable U.S. companies to establish and maintain dominance in information storage and handling technologies. These research issues are quite broad and cut across the spectrum of materials and devices.

Process Integration

Process integration is the key challenge in the design of efficient and cost-effective manufacturing processes for electronic, photonic, and recording materials and devices. Currently, these products are manufactured by a series of individual, isolated steps. If the United States is to retain a position of leadership, it is crucial that the overall manufacturing methodology be examined and integrated manufacturing approaches be implemented. Historically, all industries have benefited both economically and in the quality and yield of products by the use of integrated manufacturing methods. As individual process steps become more complex and precise, the final results of manufacturing (e.g., yield, throughput, and reliability) often depend critically on the interactions among the various steps. Thus, it becomes increasingly important to automate and integrate individual process steps into an overall manufacturing process.

The concepts of chemical engineering are easily applied in meeting the challenge of process integration, particularly because many of the key process steps involve chemical reactions. For example, in the manufacture of microcircuits, chemical engineers can provide mathematical models and control algorithms for the transient and steady-state operation of individual chemical process steps (e.g., lithography, etching, film deposition, diffusion, and oxidation), as well as models and associated control algorithms for the interactions between one process step and another, and ultimately between processing and the characteristics of the final device. As another example, in microcircuit manufacture, chemical engineers can provide needed simulations of the dynamics of material movement through the plant, and thus optimize the flow of devices (or wafers) through a fabrication line.

Reactor Engineering and Design

Closely related to challenges in process integration are research challenges in reactor engineering and design. Research in this area is important if we are to automate manufacturing processes for higher yields and improved product quality. Contributions from chemical engineers are needed to meet this challenge—processes such as CVD, epitaxy, plasma-enhanced CVD, plasma-enhanced etching, reactive sputtering, and oxidation all take place in chemical reactors. At present, these processes and reactors are generally developed and optimized by trial and error. A basic understanding of fundamental phenomena and reactor design in these areas would facilitate process design, control, and reliability. Because each of these processes involves reaction kinetics, mass transfer, and fluid flow, chemical engineers can bring a rich background to the study and improvement of these processes.

An important consideration in reactor design and engineering is the ultraclean storage and transfer of chemicals. This is not a trivial problem; generally, the containers and transfer media are the primary sources of contamination in manufacturing. Methods are needed for storing gases and liquids, for purifying them (see the next section), and for delivering them to the equipment where they will be used—all the while maintaining impurity levels below 1 part per billion. This purity requirement puts severe constraints on the types of materials that can be used in handling chemicals. For example, materials in reactor construction that might be chosen primarily on the basis of safety often cannot be used. Designs are needed that will meet the multiple objectives of high purity, safety, and low cost.

The ultimate limit to the size of microelectronic devices is that of molecular dimensions. The ability to "tailor" films at the molecular level—to deposit a film and control its properties by altering or forming the structure, atomic layer by atomic layer—opens exciting possibilities for new types of devices and structures. The fabrication of these multilayer, multimaterial structures will require more sophisticated deposition methods, such as MBE and MOCVD. Depositing uniform films by these methods over large dimensions will require reactors with a different design than those currently used, especially for epitaxial growth processes. The challenge is to be able to control the flow of reactants to build layered structures tens of atoms thick (e.g., superlattices). To achieve economic automated processes, the reactor design has to allow for the acquisition of detailed real-time information on the surface processes taking place, fed back into an exquisite control system and reagent delivery system. This problem gives rise to an exciting series of basic research topics.

Ultrapurification

A third research challenge that is generic to electronic, photonic, and recording materials and devices stems from the need for starting materials that meet purity levels once thought to be unattainable.

This need is particularly acute for semiconductor materials and optical fibers. For semiconductor materials, the challenge is to find new, lower cost routes to ultrapure silicon and gallium arsenide, and to purify other reagents used in the manufacturing process so that they do not introduce particulate contamination or other defects into the device being manufactured. For optical fibers, precursor materials of high purity are also needed. For example, the $SiCl_4$ currently used in optical fiber manufacture must have a total of less than 5 parts per million of hydrogen-containing compounds and less than 2 parts per billion of metal compounds. Either impurity will result in strong light absorption in the glass fiber. For magnetic media, the challenge is to separate and purify submicron-sized magnetic particles to very exacting size and shape tolerances.

A variety of separation research topics have a bearing on these needs. These include generating improved selectivity in separations by tailoring the chemical and steric interactions of separating agents, understanding and exploiting interfacial phenomena in separations, improving the rate and capacity of separations, and finding improved process configurations for separations. These are all research issues central to chemical engineering.

Chemical Synthesis and Processing of Ceramic Materials

The traditional approach to creating and processing ceramics has been through the grinding, mixing, and sintering of powders. Although still useful in some applications, this technology is being replaced by approaches that rely on chemical reactions to create a uniform microstructure. Among the typical examples of such an approach would be sol–gel and related processes. A tremendous opportunity exists for chemists and chemical engineers to apply their detailed knowledge of fundamental chemical processes in developing new chemical routes to high-performance ceramics for electronic and photonic applications.

Deeper involvement of chemical engineers in manufacturing processes for ceramics may be particularly important in the eventual commercialization of metal oxide superconductors. The current generation of such superconductors consist of structures that are formed during a conventional ceramic synthesis. It is by no means clear that the structures that may produce optimal performance in such superconducting ceramics (e.g., room-temperature superconductivity, capacity for high current density) are accessible by these techniques. Rational synthesis of structured ceramics by chemical processing may be crucial to further improvements in superconducting properties and in affording efficient large-scale production.

Deposition of Thin Films

Precise and reproducible deposition of thin films is another area of great importance in the chemical processing of materials and devices for the information age.

In microelectronic devices, there is a steady trend toward decreasing pattern sizes, and by the end of this decade the smallest pattern size on production circuits will be less than 1 μm. Although the lithographic tools to print such patterns exist, the exposure step is only one of a number of processes that must be performed sequentially in a mass production environment without creating defects. Precise and uniform deposition of materials as very thin films onto substrates 15 cm or more in diameter must be performed in a reactor, usually at reduced pressure. Particulate defects larger than 0.1 μm in these films must be virtually nonexistent. Low-temperature methods of film deposition will be needed so that defects are not generated in previous or neighboring films by unwanted diffusion of dopants.

For optical fibers, improved control over the structure of the thin films in the preform will lead to fibers with improved radial gradients of refractive index. A particular challenge might be to achieve this sort of control in preforms created using sol–gel or related processes.

Another challenge in depositing thin films on optical fibers occurs in the final coating step. Improved coating materials that can be cured very rapidly, for example, by ultraviolet radiation, are needed for high-speed ($>$ 10 m/s) fiber-drawing processes. Both glassy and elastomeric polymers with low glass transition temperatures are needed for use over temperatures ranging from -60 to 85°C or higher. Hermetic coatings are required to avoid water-induced stress corrosion of silica glasses, which proceeds by slow crack growth. Materials under study include silicon carbide and titanium carbide applied by chemical vapor deposition, as well as metals such as aluminum. A 10-fold increase in the rate at which such coatings can be applied to silica fiber during drawing is needed for commercial success. These coatings must be pinhole-free, have low residual stress, and adhere well. Hermetic coatings will also be needed to protect the moisture-sensitive halide and chalcogenide glasses that may find use in optical fibers of the future because of their compatibility with transmission at longer wavelengths.

Considerable progress in the science and technology of depositing thin films is needed if the U.S. recording media industry is to remain competitive with foreign manufacturers. New, fully automated coating processes that will generate high-quality, low-defect media are needed. Not only must considerable effort be mounted in designing hardware and production equipment, but it is also necessary to develop complex mathematical models to gain an understanding of the kinetic and thermodynamic properties of film coating, as well as the effect of non-Newtonian flow and polymer and fluid rheology. A better understanding of dispersion stability during drying, as well as of diffusion mechanisms that result in intermixing of sequential layers of macromolecules, is important.

Modeling and the Study of Chemical Dynamics

A challenge related to the problems of reactor design and engineering is the modeling and study of the fundamental chemistry occurring in manufacturing processes for semiconductors, optical fibers, and magnetic media. For example, mathematical models originally developed for continuously stirred tank reactors and plug-flow reactors are applicable to the reactors used for thin-film processing, and can be modified to elucidate ways in which thin-film reactors can be improved. Enabling these models to reach their full descriptive potential will require detailed studies of the fundamental chemical reactions occurring on surfaces and in the gas phase. For example, etching rates, etching selectivity, line profiles, deposited film structure, film bonding, and film properties are determined by a host of variables, including the promotion of surface reactions by ion, electron, or photon bombardment. The fundamental chemistry of these surface reactions is poorly understood, and accurate rate expressions are particularly needed for electron-impact reactions (i.e., dissociation, ionization, or excitation), ion–ion reactions, neutral–neutral reactions, and ion–neutral reactions. The scale and scope of the effort devoted in recent years to understanding catalytic processes needs to be given to research related to film deposition and plasma etching. Until a basic understanding is achieved of chemical reactions occurring at the surface and in the gas phase, it will be difficult to develop new etching systems.

Research related to this area has had a demonstrable impact on recent innovations in plasma processing. Five years ago, it was well known that a fluorine-containing plasma etches silicon at a rate significantly greater than the rate for SiO_2, thus offering significant advantages for fabricating integrated circuits. However, well-controlled processes could not be developed that would perform in a production environment. The work of chemical engineers in elucidating the relevant chemical reactions and their kinetics was crucial to the identification of the important chemical species in the etching process, their reaction pathways, and, in addition, to the discovery that the organic polymer photoresist contributed to plasma chemistry and selectivity in important ways. These studies led to new, improved plasma processes that are currently being used in production.

For magnetic media, mathematical models could enhance our fundamental understanding of the manufacturing processes used to make uniform high-purity magnetic particles. Models for the kinetics and mechanisms of reactions and an improved understanding of the thermodynamics of producing inorganic salts are required.

Environment and Safety

Safety and environmental protection are extremely important concerns in all of the high-technology areas already discussed. They present demanding intellectual challenges. The manufacture of materials and devices for information handling and storage involves substantial quantities of toxic, corrosive, or pyrophoric chemicals (e.g., hydrides and halides of arsenic, boron, phosphorus, and silicon; hydrocarbons and organic chlorides, some of which are cancer suspect agents; and inorganic acids). Unfortunately, the industries involved in manufacturing these materials and devices have only recently begun to employ significant numbers of chemical professionals, and have suffered from a lack of expertise in the safe handling and disposal of dangerous chemicals. Recent studies in California indicate that the semiconductor industry has an occupational illness rate 3 times that of general manufacturing industries. Nearly half of these illnesses involve systemic poisoning from exposure to toxic materials. Problems with groundwater contamination in Santa Clara County, California, have also raised concerns about how well the semiconductor industry is equipped to handle waste management and disposal. If the semiconductor and other advanced material industries are to continue to prosper in the United States, it is important that the expertise of chemical engineers be applied to every aspect of chemical handling in manufacturing, from procurement through use to disposal.

RECOMMENDATIONS

Pursuing the research frontiers discussed in the preceding section will significantly benefit our national standard of living, defense, education, and trade balance. How can we best use resources to foster work in these areas, and to foster communication and collaboration among researchers in industrial, academic, and federal laboratories?

The following goals should be set for improving national research capabilities that will result in improved manufacturing processes for electronic, photonic, and recording materials and devices.

- Federal agencies involved in the support of basic materials research (for example, the National Science Foundation [NSF], the U.S. Department of Energy, and the U.S. Department of Defense) should consider undertaking new initiatives in the support of fundamental research addressing the generic intellectual issues in the chemical processing of electronic, photonic, and recording materials and devices (see the preceding section).

- It is particularly important to involve chemists and chemical engineers in research related to ceramic synthesis and processing. Researchers trained in traditional approaches to ceramic materials may not have the optimal background to pursue the new challenges in the molecular design, synthesis, and engineering of ceramics.
- Fundamental research and training to meet the needs of industry for chemical process engineers and scientists should be broadly based in many academic institutions, for two reasons. First, many of the research areas mentioned in the preceding section lend themselves to research groups led by single principal investigators or by small teams of two or three coprincipal investigators. The magnitude of support given to such research groups should be enhanced to provide access to the sophisticated instrumentation needed to pursue effective research on fundamental phenomena important to research areas such as separations, processing, and reactor design. Second, the demand from the electronics industry alone for personnel with chemical backgrounds is sufficiently large that the founding of a few large centers is not likely to meet the need. Some chemical engineering departments, for example, are reporting that up to a quarter of their baccalaureate graduates are being hired by electronics firms.
- University research, particularly in engineering, should be effectively coupled to industry through collaborative mechanisms. Industry has been the prime mover in advancing technology in materials and components for information storage and handling, and will remain so for the foreseeable future. It is important, then, for university research groups to develop and maintain good communication with counterpart research groups in industry. The NSF Engineering Research Centers program and Industry–University Cooperative Research program are two effective means to stimulate such communication and collaboration.
- A few of the existing NSF Engineering Research Centers are addressing research issues that touch on the topics covered in this briefing. Where appropriate, these centers should be encouraged to seek broader participation in their programs from chemical scientists and engineers.
- The current undergraduate curriculum in chemical engineering, although it provides an excellent conceptual base for graduates who move into the electronics industries, could be improved by the introduction of instructional material and example problems relevant to the challenges outlined in this briefing. This would not require the creation of new courses, but the provision of material to enrich existing ones. Seminal texts often serve to redefine the boundaries of a discipline and to direct teaching and research toward new frontiers. The NSF should create incentives for select researchers at the cutting edge of chemical engineering to write the next generation of textbooks for their field.

The existing network of programs in funding agencies do not address some important problems in the generation and transfer of expertise and ideas from the research laboratory to the production line. For the technologies discussed in this report, a key role in generating new process concepts and equipment is played by a large number of relatively small firms. These firms are generally not in a position to make financial contributions to Engineering Research Centers or to retain academic consultants, yet face important research problems in fundamental science and engineering that would benefit markedly from the insights of academic researchers. The United States could significantly boost its competitive position in the technologies discussed in this report by facilitating information transfer between academia and this segment of industry. The problem for funding agencies with an interest in promoting U.S. capabilities in this area is how to create incentives for academic researchers to seek out and forge links to the small firms that stand at the crucial step between laboratory research and production processes. Examples of two possible mechanisms that provide these incentives follow.

- Agencies such as the NSF could create a new sabbatical award for academic researchers to spend up to a year in the laboratory of a small process technology firm. The rationale for such a program would be both to provide a critical sector of U.S. advanced process technology firms with the latest insights from university research, and to provide university researchers with insights into the ways in which fundamental science and engineering can contribute to the practical problems of high-technology processing of materials and devices.
- A limited number of "incubator research programs," providing state-of-the-art facilities cohabited by researchers from advanced process technology firms and researchers in process engineering associated with universities, could be set up in close proximity to academic research campuses. Key to these programs would be the contribution by industry of high-quality research personnel, in lieu of providing financial support for academic research conducted under these programs. The government might provide a significant portion of the facility costs to those university applicants that could assemble a critical mass of researchers from their own departments and from high-technology firms. The concept of "incubators" is not novel, and past attempts to translate such a concept into reality have met with success on some occasions and failure on others. The panel believes that a solicitation of proposals emphasizing interactions between academia and the small process technology companies that are capital-poor but problem-rich would prove a worthwhile experiment with a good chance of success.