NISTIR 5777

Beyond the Technology Roadmaps:

An Assessment of Electronic Materials Research and Development

Edited by

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March 1996

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NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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FOREWORD

I am delighted to present this report, *Beyond the Technology Roadmaps: An Assessment of Electronic Materials Research & Development.* It was prepared in recognition of the critical importance of materials to the U.S. electronics industry and it provides an assessment of electronic materials R&D issues and needs in the context of U.S. national competitiveness. It is my hope the information contained in this report will catalyze additional interactions between the public and private sectors in electronic materials and will provide a focus for appropriate materials R&D.

The report is the product of the Electronic Materials Working Group (EMWG), which was organized to support the activities of both the Materials Technology (MatTech) and the Electronics Subcommittees of the Committee on Civilian Industrial Technology (CCIT). The CCIT is one of nine primary committees of the National Science and Technology Council (NSTC) that were established to coordinate science and technology policies, and R&D strategies across the Federal government in terms of broad national goals.

The EMWG membership consists of representatives from Federal departments and agencies that support programs in electronics. They include the Department of Commerce Technology Administration and National Institute of Standards and Technology, the Department of Defense Advanced Research Projects Agency and Naval Research Laboratory, the Department of Energy, the National Aeronautics and Space Administration, the National Science Foundation, and the Office of Science and Technology Policy.

Most importantly, I wish to thank the men and women from industry and academia who worked side-by-side with the EMWG and whose ideas and recommendations form the basis of this report. In addition, I would like to acknowledge the outstanding leadership of Dr. Robert Leheny, ARPA , chairman of the EMWG, and the hard work of all the EMWG members who helped bring this project to fruition.

Lyle H. Schwartz
Chairman
Materials Technology Committee

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PREFACE

This report captures the findings of the December 6-7, 1994 industry-government-university *Workshop on Electronic Materials* held in Dallas, TX that was planned by the MatTech Electronic Materials Working Group (EMWG) (see Appendix B) in conjunction with U.S. industry. It provides a summary of the dominant electronic materials issues facing U.S. industry and contains recommendations critical to the advancement and competitiveness of the U.S. electronics and materials industries.

Established to support the activities of MatTech and the Electronics Subcommittees of the NSTC's Civilian Industrial Technology Committee, the objectives of the EMWG are to:

- investigate methods to team industry groups and government agencies to create a national strategy for Federal investment in high leverage and/or critical materials and material processing technologies to significantly enhance U.S. competitiveness in electronics and supporting industries; and
- provide a forum, knowledge base, and recommendations for coordinating efforts of appropriate government agencies.

The approach used to achieve these objectives are to:

- review recent industry and government reports focused on the current status and future plans of various segments of the electronics industry;
- co-sponsor a workshop with the electronics industry, electronics support industries, and the university research community to identify short and long term industry materials needs; and
- assess the role that government programs can have in terms of support for critical industry needs.

This report began in 1994 when the EMWG directed its focus on materials issues for five major electronic technologies identified in the National Electronics Manufacturing Initiative (NEMI). NEMI is a public-private partnership focused on leveraging limited resources in electronics manufacturing for sustained national security and economic growth. Initiated through the activities of the NSTC Electronics Subcommittee and U.S. industry, the technical focus of NEMI is the manufacturing of electronic information products that connect to information networks. The performance capability of these information products is heavily dependent on the properties and performance of the electronic materials from which they are built

The five technologies encompassed by the NEMI framework and this report are microelectronics (VLSI), radio frequency (RF) and microwave electronics, photonics, mass storage, and module interconnection. In addition, materials characterization and materials research, two areas essential to the discovery, understanding and utilization of materials, are included. Each of these topics has been the subject of several industry and/or government reports aimed at evaluating the current status of the U.S. electronics industry (Appendix C). Many also go so far as to include technology roadmaps that identify the time scale associated with industry's future needs. The EMWG reviewed these reports within the context of materials issues relative to the seven technology categories listed above and felt that further effort was needed to develop a comprehensive assessment of electronic material needs.

In October, 1994 the EMWG met with representatives of the various industry associations responsible for generating these reports to plan an industry, government, university workshop to review and assess materials-specific issues critical to progress and competitiveness in electronics (Appendix D). At that time, additional reports pertaining to electronic materials were recommended by the industry representatives (Appendix E). With the aid of these organizations, a two day *Workshop on Electronic Materials* was organized (Appendix F). In total, 42 industry, 18 University, 17 Government Laboratory and 8 Government agency representatives attended the workshop (Appendix G).

During the workshop, individual presenters, knowledgeable about materials requirements for each of the topical areas, presented a preliminary view of the important materials issues in an opening plenary session. The workshop then broke into seven working committees for detailed discussion of the topic areas. In these breakout committees a consensus was reached on critical material issues and their relative priorities. The workshop reconvened on the second day for feed-back on the results of the working committee discussions and for general discussion of the issues. The presenters' visual materials, materials generated and used during the feed-back session, and recordings of the discussions that took place, formed the basis for this report.

In completing this report, the EMWG would like to thank the many people from industry and academia who participated in the planning and execution of the December 1994 workshop, and who contributed to the preparation of this report. Without their support, this activity could not have been undertaken. With their support, a comprehensive review of electronic materials issues now exists. Thank you.

Electronic Materials Working Group

EXECUTIVE SUMMARY

Materials are the foundation of the electronics industrial enterprise.

Figure 1 illustrates the "Technology Food Chain" which formed the basis for the EMWG's analysis of the role of materials in supporting information age electronics. At the beginning of this chain are basic materials science and technology and the starting materials used to produce application specific materials structures, for example bulk crystals, epitaxial films, dielectric materials, metals for contacts and interconnects, etc.. These materials structures are processed into devices for subsequent packaging into subsystem modules. These modules in turn are interconnected and assembled into systems designed for specific applications that support the services which provide the revenues fueling the information economy.

An effective industrial/economic strategy requires that no weak link exist in this food-chain.

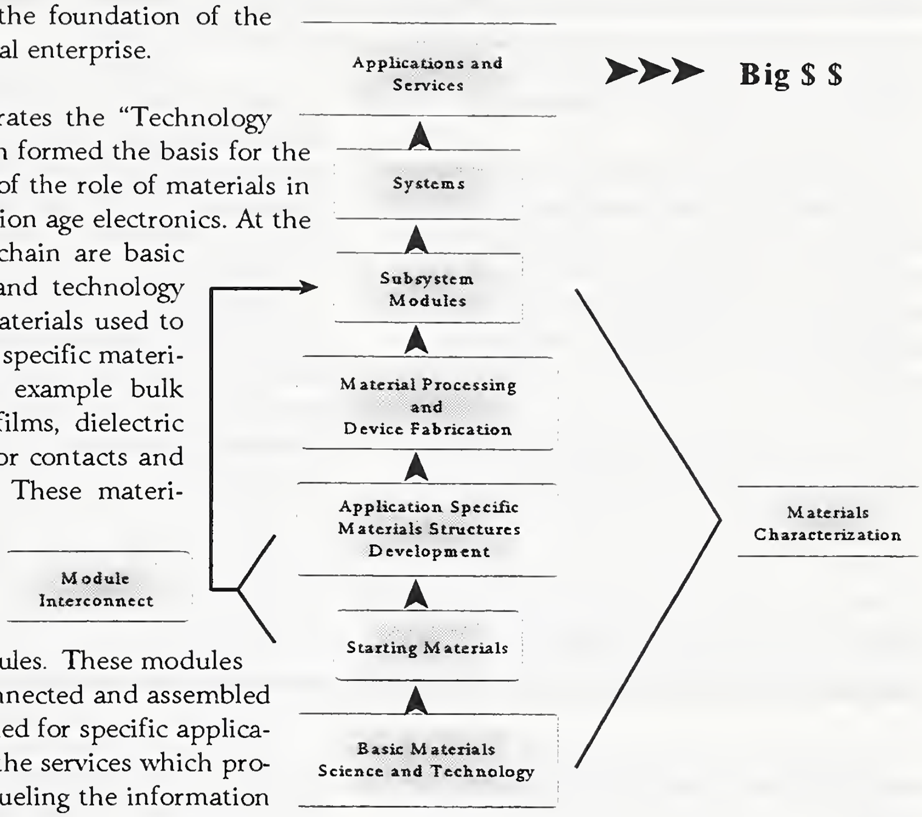

Figure 2: Technology Food Chain

FINDINGS

➢ **There is a continuing research challenge across the microelectronics industry to maintain the trend towards increased materials complexity and reduced device feature size.**

Improving the quality of starting materials and increasing the dimensions and quality of substrates on which devices are fabricated, or mounted, are critical to all applications. Competitive production of electronic devices and modules requires cost effective methods for maintaining control of local material composition and properties for films deposited over large areas, and the processing of these films while maintaining strict dimensional tolerances relative to the smallest device feature size.

To meet these challenges, research is required for improving the quality of starting materials, maintaining the required control of material deposition and processing, and developing tools for characterizing and processing materials with ever greater precision.

➢ **The microelectronics research community in the U.S. has undergone profound changes in the last 5-10 years as major industrial laboratories have reduced their support for advanced research and limited their efforts to solving more near term problems.**

This has resulted in an increasing reliance on universities and Federal laboratories for materials research and development. Weakened in the process are the traditional linkages that existed between research groups and manufacturing centers.

➢ **The guidance that close coupling between researchers and manufacturers provided may in the future be largely provided by industry wide technology road mapping led by key industrial associations.**

For this process to be successful, significant effort will be required to define and quantify the role of roadmapping in setting materials research agendas and to ensure that government support for unanticipated, revolutionary breakthroughs remains available.

Recommendations

➢ **To support the continuing push towards increased material complexity and reduced device feature size, the U.S. government should work to create an environment that encourages electronics companies to increase their participation in electronic materials research and development.**

This may be effected, for example, by continuing to promote industry-led pre-competitive research consortia, and by creating centers of excellence in materials research, materials processing, and materials characterization that require collaboration between industry, universities, and Federal laboratories.

➢ **Long term goals should be focused on structuring the traditional industry, university, and Federal lab materials research community to assure effective coordination of research to meet the future needs of the electronics industry.**

To this end the Electronics Materials Working Group recommends that a dialog begin on how research needs identified through industry technology roadmapping can provide guidance for future government research investments while ensuring that breakthrough ideas are recognized and provided with adequate support.

WORKING COMMITTEE SUMMARIES

MICROELECTRONICS (VLSI)

Critical microelectronics materials issues and needs were identified in the National Technology Roadmap for Semiconductors (NTRS) [1] for VLSI development over the next few generations. The materials requirements identified are those that will allow the scaling laws that govern CMOS design to enable reduction in transistor dimensions down to dimensions where the physics governing transistor action no longer are adequate (estimated to be at gate lengths of ~0.1 μm). This will require continued developments in sub-micrometer lithography and ancillary materials, dielectric materials adequate for gate insulators and on-chip memory, development of materials for low power non-volatile semiconductor memories, materials for advanced packaging, dopant control to produce the shallow junctions, and approaches to enhance power dissipation (heat removal), such as SOI materials. In parallel with these developments, continued increases in wafer diameter are envisioned generating a need for continued development of processing equipment to handle these larger wafers. Materials for high temperature electronics and other special applications, and the means to process these materials, need to be developed.

PHOTONICS

A generic set of materials processing and characterization technologies capable of meeting requirements for the manufacture of photonic components was identified. The diverse range photonic devices for advanced applications, from telecommunications (telecom) and data communications (datacom), to sensors, imaging, displays, optical storage and printers, each have unique materials and materials processing requirements. This includes InP, silica glass fiber and electro-optic materials for telecom applications; GaAs and other materials capable of short wavelength (red to blue) emission; plastic fiber and related materials for datacom and storage applications; visible emitter materials, including newly demonstrated GaN and polymers for LEDs; and large area liquid crystal display and other technologies for flat panel displays. These technologies require continued improvements in materials design, processing and characterization to meet future market needs.

RF AND MICROWAVE ELECTRONICS

RF and microwave electronic technologies are positioned to contribute dramatically to the exploding wireless communication markets. A goal for this market segment to develop a sufficiently large commercial RF-IC market to sustain development of its own infrastructure. RF and microwave electronics has historically had its principal focus on meeting markets defined by military systems requirements, has relied on adapting silicon processing equipment to the fabrication of GaAs based circuits, and has continued development of GaAs material structures for optimizing transistor performance. With GaAs wafer dimensions one to two generations behind silicon, there is concern that adequate processing equipment will not be available in the future. Further out, the introduction of alternative materials offers the potential for enhanced power dissipation and low noise performance for conventional appli-

[1] *National Technology Roadmap for Semiconductors*, Semiconductor Industry Association, 4300 Stevens Creek Blvd., Suite 271, San Jose, CA 95129, phone: (408) 246-2711.

cations (InP), and improved high power, high temperature performance (SiC or GaN). One difficulty for sustained development of III-V materials for RF applications is the emergence of silicon devices for lower frequency, $\nu<5$ GHz, IC applications. This has the effect of splitting the market.

Mass Storage

To maintain and strengthen the U.S. industry market position in mass storage, continued development of lower cost, higher density storage media for magnetic and optical disc and tape storage is imperative. These objectives reflect a recognition that there is still significant potential for increasing storage density based on improvement in materials. However, there are significant challenges in design of media and media access technologies to facilitate exploitation of the high resolution that these memory densities represent. Future technologies, based on short wavelength lasers for optical disc, integrated head designs for fast access, and large area semiconductor (FLASH) memory, must also be investigated. Advanced optical technologies are recognized as potentially significant means for achieving high density mass storage, but are not mature enough to meet short term needs.

Module Interconnection

Electrical interconnection at the module level requires enhanced system performance that can match chip level performance. The critical challenge is to maintain strict performance control, such as dimensional stability, over large areas. Even greater requirements for performance control exist for interconnection in optical systems. The immediate objective of the U.S. industry is to recapture significant lost market share by aggressively meeting price, reliability, portability and performance requirements of the world market place. Critical materials challenges include developing low dielectric constant materials for high frequency applications, dimensionally stable polymer structures, moisture resistant resins, conductive adhesives, photoimageable dielectrics and photoresist materials, and polymer underfills and solders for long term reliability.

Materials Characterization

Characterization of electronic/photonic materials requires further development of high-quality, low-cost, reliable, instrumentation, to assess critical attributes of the materials used to fabricate products at all stages. Developmental endeavors place the greatest demand on materials characterization. For low volume production, process and products need to be continuously monitored, preferably in real time by *in situ*methods. For high volume manufacturing, the cost of characterization is typically great enough that the objective is to fine tune processes until continuous monitoring is not necessary. Experience shows that measurement tools developed as part of the materials research process have evolved into standard diagnostic tools over time. Today's techniques enable measurement of material structures on an atomic scale and major challenges are the high cost of state-of-the-art tools, cost of maintaining in-house capabilities, and the corresponding critical expertise needed to collect and interpret the data to provide quality control over all materials used in electronic device manufacturing.

Research Opportunities

Efforts are needed to continue to push the frontiers of basic understanding of material behavior, the physics and chemistry of materials underlying electronic and photonic device technologies, and the capability to design material and device structures at the atomic or molecular scale. The key challenge is how to accomplish this given the full suite of sophisticated tools required may extend beyond the financial resources of any single institution, private company, university or government laboratory. A possible alternative is development of modeling and simulation tools that accurately reflect physical phenomena and that can reduce the cost of developing atomic scale devices and fabrication capabilities. The current trend of reduced levels of industry support for in-house, long term research is resulting in reduced focus within the remaining research community. Significant restructuring of the traditional relationship between private industry, university and government laboratories may be required to ensure the greatest benefit from research investments.

WORKING COMMITTEE REPORTS

MICROELECTRONICS

INTRODUCTION

The semiconductor electronics market is a $ 100B a year world-wide market. Silicon-based microelectronics (98% of this market) has been the linchpin of the multi-trillion dollar electronics industry in America. Revolutionary advances in this technology have been the engine driving the technological revolution of the last 40 years leading to higher standards of living and creating a bootstrap effect in many other high technologies. As such, it has been the subject of considerable study by government and private sector organizations. The Semiconductor Industry Association (SIA), Semiconductor Equipment and Materials International (SEMI) and SEMATECH all have launched major studies and the SIA has prepared a technical plan, or roadmap, the National Technology Roadmap for Semiconductors (NTRS), to guide development in this field. While documents such as the NTRS provide a technological focus for future activity, the mechanism for implementing these plans is not spelled out in any detail. The purpose of this working committee is to provide a framework for joint government / industry support of materials R&D necessary to retain national competitiveness in microelectronics technologies. The world-wide semiconductor materials industry today is approximately $15B, of which the U.S. market share is just 8%.

The working committee reviewed the specific areas of materials technology, discussed these technologies in light of NTRS requirements, and evaluated the current development plans for each technology.

PRESENTER AND DISCUSSION SUMMARY

The working committee addressed what it considered to be critical areas of silicon-based materials technology. The areas discussed coincided roughly with the NTRS technical working groups (TWG). TWG summaries are included below. The committee concluded that the material topics listed below were all of highest priority and needed to be addressed to ensure national competitiveness in the future.

Silicon

The critical issue for silicon is one of supply and quality assurance. For large diameter wafers (200-300 mm), high quality epitaxial growth layer is a concern. The U.S. does not have a significant U.S.-owned large wafer supplier. Quality or the incoming supply of wafers can not be assured even if epitaxial growth is performed in-house or by a separate stand-alone on-shore vendor. High quality epitaxial material is needed because it has a significant impact on yields and circuit performance. The committee believes this is a short or near term activity (about 3-6 years until the start of manufacturing for 300 mm wafers). The committee proposes work in this area with a significant focus early in the process.

Silicon on Insulator (SOI)

The issue here is the availability of quality materials at an affordable price when they are needed by the industry. The benefits are improved electrical isolation and a significant improvement in circuit density, which would lead to a substantial cost/density benefit. These benefits can't be realized until the manufacturing quality, availability and price of

SOI wafers is under control. The introduction of this technology would have a major impact on power device technology as well. SOI also has the opportunity to provide significantly improved isolation for DRAMs among other things. There are Japanese papers that describe the benefit of SOI for 256 Megabit memories. SOI technology is expected to become commercially significant in the 1996-98 time period.

Interlayer Dielectric (ILD) Materials

The concern is that currently available materials used as inter-layer dielectrics are severely limiting circuit switching speed. This ranks as very important for microprocessor ICs and very fast access DRAMs of the future. Materials issues are the need for a thin, low dielectric material ($1.5 \leq \epsilon \leq 3.0$ is desirable) that is free of pinholes and that has an acceptable breakdown voltage. The material must also be robust enough to support pattern definition in a manufacturing environment and exhibit process stability and compatibility with new metal systems, such as copper, etc. The material must also exhibit reproducible characteristics and reliability issues such as adhesion, and moisture absorption. These are near and middle term needs (3-6 years, and 6-10 years).

High Dielectric Constant Materials

New materials are required for process compatibility with existing technology. The major benefit here is for on-chip capacitors where high capacitance is needed, such as in DRAM storage cells and non-volatile semiconductor memories (NVSM). Also high dielectric constant materials are needed for on-chip power conditioning circuits. These are near and middle term needs (3-6 years, and 6-10 years).

Photo Resists

Sensitive photo resist materials are needed for deep UV, 248 nm and 193 nm light source wavelengths. In the case of 248 nm source wavelengths existing resists are not user friendly. Resists optimized and usable in a manufacturing environment for 193 nm source lithography do not exist at the present time and must also be developed. Resists that are suitable for mask making applications at 0.25 micrometer and 0.18 micrometer that are e-beam writable need to be developed. The key properties needed are high sensitivity to electrons and stability over very long writing times. In summary, 248 nm resists are marginal at present and 193 nm resist are not available. These materials limitations are impeding the manufacturing capability of 0.25 - 0.18 micrometer feature size ICs. The concept of creating a U.S.. Center of Competency for Resist Materials was discussed. It could be resident at a government laboratory or a university. It would serve to support the user community over a long period of time and would develop and build a set of skills and tools to do the research for these materials ensuring their availability when needed.

Masks

Availability and quality are the key present issues. Materials development issues are in the characteristics of fused quartz and pellicles. For 248 nm lithography, the issue is availability of suitable mask blanks including both source of quartz and polishing (no U.S. sources are currently available). For 193 nm, optical damage to the optics and mask by the source is the primary issue. The pellicle materials in both cases require quality and durability. A 3-6, and 6-10 year development phase is needed for 0.18 micrometer, and 0.25 micrometer manufacturing and volume development, respectively (and 0.12 micrometer to follow).

Thin Gate Oxides

Extensive R&D is needed to produce high uniformity and low defect density high breakdown voltage films with scaled performance as feature size dimensions shrink from 0.25 to 0.12 micrometer. This applies to both film yield and reliability. In the areas of gate insulators and storage insulators, the issue is to avoid oxide tunneling for applications involving conventional gate insulators and interpolysilicon dielectrics while enhancing tunneling in both the "floating gate" and silicon-oxide-nitride-oxide-silicon (SONOS) type NVSMs. This is an area of materials development in which advances are needed over the long term. The panel believes there are some materials in the short term that could be brought into a manufacturing environment. But, in general, this technology area needs a concerted long term research activity and a manufacturing exploitation.

Contact Resistance and Shallow Junctions for Contact Materials

Electrical performance and yield are the primary issues for these materials. This is a continuing area of development.

Interconnect Materials

High electrical conductivity and high reliability metals are critical needs for on-chip interconnects. Interconnect electrical performance, reliability and yield are the primary issues. This is also a continuing area of development. The committee had a long debate about interconnect metals. Alternative metal systems, such as copper technology, are being evaluated for use in the near future. However, various additional alloys should continue to be investigated for the long term.

Packaging

The committee addressed packaging principally from the point of view of microprocessor needs, i.e. low cost, high pin count, and high thermal conductivity requirements. A "smart" package is needed that can allocate power and provide variable interconnect density. Again, middle term and near term activities are essential. There is a fair amount of R&D taking place on plastic package materials, but little or no work going on from a ceramic perspective, either for single or multiple chip packaging.

Breakthrough materials, i.e., innovative materials that would create a paradigm shift in the semiconductor integrated circuit industry were discussed. Examples of such materials include Si/Ge for high speed/power densities; wide bandgap semiconductors for high temperature electronics and optoelectronics (i.e. SiC and GaN); and micro-electromechanical (MEMS) systems for novel material properties. None of these items are envisioned in the NTRS. This is, perhaps, a significant omission. The concern is that it is easy to identify incremental extensions in the materials of today that are needed for improved performance or manufacturing yields. It is very important that a fraction of the research focus on materials research be maintained that could create an entirely new approach to electronic components. However, the issue of paradigm shifts and the impact of these shifts on the technology base could not be fully discussed within the limited time of this workshop. So, for example, the potential for the optics-to-x-ray lithography shift was not discussed, nor were the attendant materials needs for this technology. This should be taken up at a later date.

Specific Issues

No amount of advanced research will truly benefit the U.S. electronics industry infrastructure without revitalization of the associated domestic materials manufacturing base. Even though the U.S. accounts for 8% of the worldwide semiconductor materials market, overall investment costs for entry plus low profit margins, create barriers to domestic infrastructure growth.

There is a recognized need for a coordinated plan for government and industry support in the general areas of semiconductor material and equipment development, something akin to MITI programs in Japan and ESPRIT and JESSI programs in Europe.

Existing roadmaps, in particular the NTRS, delineate (with some possibly significant omissions) the industry-desired material development path for silicon-based devices. One possibly significant omission from the NTRS is treatment of Si:Ge R&D for high-speed heterojunction transistors.

The industry, as represented by SEMATECH, focuses on short-to-mid term needs and enhancements. In contrast, industrial R&D investment drops significantly as the time horizon moves further beyond the current IC generation.

Important materials issues confront low-power, low-voltage NVSMs if they are to achieve cost competitiveness with magnetic disk systems. These products will have wide application in portable military and consumer product markets. Achieving the so-called "semiconductor memory disk" will enable breakthrough reductions in size, weight, power dissipation, speed, reliability, and latency time in future microelectronics products.

Summary

The major outcome of the working committee's effort is that a request be disseminated to appropriate government and industry management organizations. The request is to recognize that, on the international scene, all major foreign semiconductor materials manufacturers can count on some coordinated government / industry effort in infrastructure support. The need for U.S. infrastructure support extends beyond considerations of "industrial policy" and government's picking winners and losers. It is a simple fact that the Nation's infrastructure requires a significant level of support if the U.S. is to succeed in world market competition. The U.S. has already lost control of most segments of the supply chain for materials essential for global leadership in electronics. New mechanisms and policies must be developed to support and stimulate domestic materials suppliers. The maintenance of our electronics infrastructure is viewed as a defense-critical need.

Along with this request is an observation that the form of this coordination requires considerable definition. Studies of the most successful infrastructure suppliers, both foreign and domestic, are necessary. Government / industry coordinators must assist in assessing and transmitting the most successful techniques to the U.S. manufacturing community at large.

SEMATECH should maintain its focus on the near-term needs of the industry. ARPA should maintain a long-term focus on research. A new relationship between U.S. government agencies and the domestic industry may be needed for global competitiveness.

Photonics

Introduction

Photonic technologies impact a broad range of information age applications spanning from electronic information collection, transmission, storage, display and hard copy reproduction. For many of these applications photonics is an enabling technology in the sense that the application would not be possible without photonic components. The Optoelectronic Industry Development Association (OIDA) has estimated that the markets for equipment enabled by optoelectronics are as large as $50B today and will grow to over $400B over the next twenty years. In 1994 OIDA published a roadmap outlining the technology developments required to achieve this growth.

The photonic materials requirements to meet these various applications are very broadly based; semiconductor materials that efficiently generate, detect, or guide light, electro-optic materials capable of modulation or deflection of light under the influence of applied electric fields, composites of glass or polymers forming optical fiber cables and waveguides, liquid crystals for displays and spatial light modulators, magneto-optic materials for optical discs, and so on. Specific material parameters important for photonic applications include bandgap energy, index of refraction and index dispersion, optical absorption, minority carrier lifetime and defects that influence lifetime or trapping of charge, etc. Which set of parameters are important to optimize for a given application is to a large extent determined by the application.

In addition, for each application there is an ideal region of the photon spectrum: near infrared light to match the low transmission loss spectra of silica fiber for telecommunications or night vision; shorter wavelength light to match photonic devices with silicon electronics and the loss spectra of plastic fibers for interconnections in data communication systems; light spanning the visible portion of the spectrum for optimum interfacing to human vision; and even shorter wavelength light to minimize spot size for optical data storage and to maximize photon energy for photo-initiated chemical processes.

Presenter and Discussion Summary

The ability to manufacture photonic components at low cost is the central challenge facing this industry. Typically, photonic components have to be affordable whether they are manufactured in large or modest volumes and therefore flexible manufacturing tools are required. As wide as the range of materials important to photonic applications is, there are significant generic issues that can be identified.

- **Epitaxial growth technology based on molecular beam epitaxy or chemical vapor deposition to deliver specific material structures.** Here, the critical issues are high quality starting materials, fundamental understanding of interfacial chemical and physical processes, *in situ* processing to reduce wafer handling in the fabrication of complex devices, and in-process measurement techniques to ensure reproducibility even on an atomic scale.

- **The availability of commercial sources of epitaxial material to supplement or replace the need for expensive in-house capabilities.** Here, the issues are to identify material structures generic enough to support merchant epitaxy support while maintaining sufficient flexibility to allow the delivery of small lots of specialized structures.

- **Development of effective low resistance electrical contacts and development of effective electrical, optical and environmental passivation technologies.**

- **Manufacture methods to efficiently produce integrated material structures, either through monolithic integration or hybrid integration of separately prepared structures.**

- **Technologies for assembly of components with optical precision into packaged sub-modules capable of presenting common interfaces to systems designers while meeting environmental requirements.**

- **Development of efficient, cost effective manufacturing technologies for non-semiconducting materials and devices based on these materials, such as, electro-optic oxides, optically active polymers, magneto-optic materials, large area liquid crystals, etc..**

There is significant similarity between the processing needs of photonics and microelectronics, and full advantage should be taken to use these already developed processes and equipment. However, a number of critical general features distinguish photonics manufacturing from microelectronics. The three-dimensional aspect of optoelectronic devices is pervasive; the importance of the vertical dimension and direction sets optics apart from planar configured microelectronics. A challenge is to develop accurate 3D models that combine semiconductor charge transport with electromagnetics while also incorporating thermal effects.

In a similar way, electrical contact issues for photonic devices can benefit from the wealth of information developed for microelectronics. However, the three-dimensional nature of photonic circuits, the large number of hetero-interfaces involved, and the diversity of materials that typically comprise photonic circuits combine to make achievement of reliable contact technology a significant challenge.

Large area fabrication also introduces unique requirements for photonics. Devices such as displays, high resolution CCD's, smart pixel arrays and integrated photonic chips incorporating interconnecting waveguides, all exceed requirements for commonly manufactured electronic chips in either linear or areal dimensions by one or two orders of magnitude. Large area fabrication also puts high demands on materials uniformity.

For many photonics applications, manufacturability is strongly tied to reproducible synthesis of highly complex materials structures, e.g. multiple layer semiconductor stacks that form mirror structures. Achievement of targeted layer thickness doesn't always ensure the desired optical output since typically both material composition and layer thickness are important. Adequate, low-cost *in situ* monitoring techniques must be developed to allow monitoring of the desired optical or electronic output of grown structures.

There is a wide diversity of materials used in photonics technology, each with different processing tolerance and requirements. Heterogeneous integration processes that allow reliable incorporation of diverse materials onto a single chip are therefore important. Process sequences must be developed that do not require exceeding the temperature limitations for maintaining the integrity of any of the materials structures. For example, polymeric materials incorporated at one point in device processing may not be capable of standing up to high temperatures or the presence of energetic radiation in subsequent processing steps.

Alternative techniques, such as epitaxial lift-off, allow the integration of disparate materials into a single circuit but these technologies put stringent demands on alignment capabilities as device structures deposited on separate substrates are integrated. Beyond the dimensional control required of lithographic and etching processes, which are clearly issues shared with microelectronics manufacture, photonic devices impose additional requirements in that small variations, or roughness in delineated features, may cause unacceptable changes in optical response or scattering losses. Finally, the packing density of devices may be low, but tight dimensional tolerances often have to be maintained over long distances.

Photonics circuit manufacturability must face not only the lack of high volume markets, unlike much of microelectronics, but where diverse materials are integrated into single chips, photonics technology may have to preclude the economic advantages of continuous processing.

The ability to manufacture photonic components at low cost is critical to creating a strong position for U.S. industry. An important technology that could help lower manufacturing costs is the use of computer modeling to accurately predict device operation and manufacturing processes. Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) models require significant investment in developing the fundamental understanding of the critical processes and will benefit from data generated using *in situ* process monitors and in-process testing. These models should be able to incorporate the electronic, optical, and structural properties of the diverse materials that may comprise a photonic circuit. Forearmed with the insights gained by modeling, more manufacturable circuits can be designed thus helping to counter the disadvantages of low volume production.

SUMMARY

This working committee identified a number of critical materials issues for photonics that need to be addressed.

Near Term

- Improved processes for precision epitaxy, including atomic scale control of base composition, doping, and defect-free interfaces.

- Development of vertical cavity surface emitting lasers (VCSELs) to exploit their relaxed alignment tolerances for coupling to fibers, improved on-wafer testing capability, and ease of fabrication of arrays.

- Requirements on materials thickness and composition of photonic devices are quite stringent (although achievable), emphasizing the importance of *in situ* monitoring strategies.

- Investment in manufacturing tool development (including software) that could lead to lower cost of fabrication.

Long Term

- New materials investigations are needed. These includes light emitting polymers, optical epoxy, wide bandgap semiconductors with negative electron affinity (NEA), and low voltage phosphors.

RF and Microwave Electronics

Introduction

The dominant material for RF and microwave applications is gallium arsenide (GaAs). Many of the challenges related to economical, high-quality growth and processing of GaAs are a direct consequence of it representing only about 1% of the overall semiconductor market which is dominated by silicon. The technology needed to produce large GaAs wafers lags that used for silicon by about ten years. Up to the present time the industry has been driven by military applications. Considerable progress has been made in the last several years in establishing a methodology and infrastructure for producing GaAs monolithic microwave integrated circuits (MMICs) through DOD programs, especially through the ARPA MIMIC program. That program, by demonstrating enormous improvements in cost and performance for GaAs MMICs and related packaged modules, has shown the feasibility for widespread DOD use of phased arrays and expendables if cost reduction momentum can be maintained. However, the exploding wireless market has made commercial and military applications comparable at present, but commercial applications may completely dominate the overall market in the near future. This places substantial pressure to produce GaAs RF and microwave devices in a cost-effective manner.

Until recently, leading GaAs MMIC manufacturers have operated relatively independently. However, the industry has now organized under the Microwave Solid State Division of the Industrial Electronics Group to form a working group for discussion of issues important to the industry. The group intends to share data which will allow it to assess the size of the industry and its market potential so that investments can be tailored accordingly.

Although GaAs dominates the RF / microwave market, there is much interest and enthusiasm for next-generation materials such as indium phosphide (InP), wide bandgap nitrides (GaN, AlN) and silicon carbide. These truly represent a microcosm of a microcosm so there are significant barriers inhibiting their market penetration. Other materials needed but often overlooked for these applications are those critical for passive components such as inductors and capacitors (for lumped-element devices and energy storage) as well as circulators and filters. Efforts are needed to drive down their cost and size and to enhance their reliability. Finally, packaging is a major and often overriding affordability issue. High volume commercial approaches are needed but need to accommodate the special thermal and performance constraints imposed by RF / microwave applications.

In summary, the industry is now in transition from being dominated by high performance, low-volume DOD applications to high-volume, "good-enough" performance commercial applications. The following sections detail dominant problems which need to be addressed to successfully make this transition while retaining the performance edge needed in DOD systems.

Presenter and Discussion Summary

Cost reduction for GaAs MMICs is inhibited by continued high costs of GaAs substrates and of epitaxial layers grown on those substrates. This is compounded further by the move toward the use of larger percentages of wafers with epitaxial layers, which more than doubles the starting wafer cost. Development efforts to reduce substrate and epitaxial layer cost and to push toward larger diameter must continue to support international competitiveness of U.S. GaAs industry and continued availability for DOD systems.

One of the most significant factors inhibiting cost reduction of GaAs devices is the limitation in wafer size. Not only would larger wafer size lower die and IC cost directly, but it would permit use of more automatic silicon IC processing and lead to higher yields. In addition to lower cost, more reproducible materials will broaden their market. Currently suppliers are making the transition from 76 mm to 100 mm diameter wafers and attempts to achieve a 150 mm diameter are currently underway. Dislocation density increases with increasing size, and utilization of current growth techniques may not be possible beyond 150 mm. This of course would limit the GaAs industry's ability in following the silicon path of reducing cost by increasing wafer size.

Epitaxial layers, e.g. InAs and AlGaAs, on GaAs substrates are commonly used to enhance RF / microwave performance. Similar materials problems exist as alluded to above for GaAs substrates but the problem in the U.S. is compounded by the limited number of domestic suppliers of epitaxial material.

A related problem exists with equipment vendors, i.e. no equipment vendors specifically address the GaAs market and thus silicon IC equipment must be employed. As the silicon industry moves to 200 mm diameters and beyond, it will have little interest in making "small" 100 mm wafer handling equipment.

As noted above, other materials are being actively pursued at the R&D level for enhanced performance. InP is attractive for its superior low-noise and power capabilities at millimeter wavelengths. SiC is being investigated for high temperature, high power applications at low microwave frequencies. The wide bandgap nitride material system promises performance beyond silicon carbide in frequency, power and power-added efficiency in addition to being more robust and radiation hard than GaAs. Because of their long range device impact, a continuing investment in this technology is essential. Wise choices will have to be made, however, regarding the appropriate time to take these advanced devices to the next step - the expensive step toward moving them into production. One of the factors that could well enhance this transition to production is the overlap in material needs with other types of applications. InP is an excellent example of such a material with strong interest by both the photonic and RF / microwave communities. A similar synergy exists with the wide-bandgap materials for optical and power applications as well as for microwave/RF applications.

Cost and size of passive components for RF / microwave applications is becoming a greater concern as the size and cost of active components shrink. For example, the filter is currently the largest and most expensive component in the cellular telephone. Circulators can consume a quarter of the total area in a TR module. Advanced material systems, innovative topologies and low cost production techniques are all required. For example, use of lumped elements (microwave capacitors and inductors) can significantly reduce size and cost. Ferrite circulators which do not require external magnets would reap similar benefits. Materials which would lead to higher density energy storage, both on-chip and off-chip, are also needed. This would reduce package size and cost. Finally, passive components, especially for energy storage, often limit the overall reliability of subassemblies and this factor must be of concern in developing new approaches.

Packaging of RF / microwave devices can pose some formidable challenges. Packages a little more than an 25.4 mm square often must dissipate 20-30 watts of power making thermal management a major issue. Very low-cost is required in commercial wireless markets, which suggests the use of organic materials. Loss, thermal management, and hermeticity are especially difficult to address in packages constructed using these materials. A low dielectric constant is also desirable to achieve efficient high-power amplifier power. In certain types of applications, e.g. active arrays, it is necessary to insert and remove packages from an assembly. Although DOD programs presently are addressing some of these issues, low-cost packaging for high volume DOD and commercial applications is still one of the most significant issues facing the industry.

The U.S. industry has established a rich array of sophisticated RF / microwave technologies, and it is particularly important to support that base by selling to the widest possible market. Government regulations can be an impediment to the export process; streamlining export regulations could facilitate dual use of military-critical process lines. The U.S. is the world leader in GaAs MMIC technology and should use this advantage exporting abroad.

Specific Issues

Near Term

- **The small size of the RF / microwave industry causes difficulties in maintaining the technology base needed.** Synergy in approach to serve the military and commercial markets is important in maintaining economy of scale. However, government regulations often tend to inhibit export and other types of dual use.

- **The rate of GaAs MMIC/digital development is limited by wafer size, wafer differences among vendors, epitaxial material cost and growth methods for 152 mm and larger wafers.**

- **Full realization of chip performance potential is limited by package interconnects and thermal resistance.**

Mid Term

- **The rate of component development for advanced military systems is limited by the availability of next generation materials, e.g. wide bandgap nitrides, InP, SiC.**

- **The cost of microwave assemblies is often driven by the size, uniformity and performance of passive components, e.g. inductors, capacitors, filters and circulators.**

Synergies

Improvements in cost, size, and weight and reliability are key factors in expanding marketplace acceptance of GaAs MMIC based subassemblies. Limited availability of advanced material systems and processes will limit component development.

Summary

Many of the problems facing the RF / microwave materials industry are a direct result of it being small in size relative to the sophisticated technologies it employs. Key suppliers tend to be small producers and often not reliable, especially for advanced materials. The GaAs industry is critically dependent on tailored silicon-oriented wafer fabrication equipment. Historically RF / microwave development has been funded by the DOD because of its military critical nature. The small size of the military market does not support an aerospace company, for example, to establish a dedicated capability for internal use only. The health of the industry is increasingly dependent on synergizing DOD oriented approaches with those which have potentially large payoff in the commercial communications industry. Government funding to support cost reduction in GaAs wafers and epitaxial deposition, next-generation semiconductor materials, passive components, and low-cost packaging materials is needed by industry for continued evolution of the RF / microwave technology base required for military critical applications. This approach is synergistic with a sustained worldwide U.S. RF / microwave industry.

Mass Storage

Introduction

Materials needs in the mass storage area are driven by seemingly insatiable market demands for increased information storage capacity and reduced storage cost. For example, current industry targets call for a 60% per year compound annual growth rate in magnetic storage densities through the end of the century. Similarly, optical storage densities are targeted to increase 20 times by the year 2000. Speaking in 1991, then Undersecretary of Commerce for Technology, Robert White, explained the importance and criticality of increasing mass storage capacities.

"Storage technology is a limiting factor in the application of other information technologies. Development of high-performance computing applications are dependent upon vast storage capabilities.....(for example).... archiving and managing the data collected from satellites are overwhelming existing storage facilities. Multi-media work stations, which are currently being developed, will store and process text, images and voice and will require significantly larger secondary storage systems.....than are currently available."

Today, a number of additional high-performance computing and storage intensive applications can be added to this list including; windows based software programs, home video on demand and all-digital high density television.

Developing the technology to address the needs of these emerging applications is important to the U.S. from both economic competitiveness and national security perspectives. The storage industry currently generates worldwide revenues of $100B and U.S. companies supply 40% of this market. Storage industry sales are projected to increase at a 25% per year compounded annual growth rate, reaching $1,000B by the year 2005. Such growth will create a significant number of high quality jobs and a level of technical capability which will dramatically enhance the performance of civilian and military information systems. Today, the U.S. has the technology lead in many mass storage materials. The following recommendations should help maintain this vital lead.

Approach to Developing Recommendations

The National Storage Industry Consortium (NSIC) was formed to enhance the competitiveness of the U.S. storage industry. Over a three year period, NSIC brought together over 80 organizations for the purposes of defining strategic performance targets or roadmaps for mass storage technologies and establishing joint, pre-competitive research activities. The Optoelectronics Industry Development Association (OIDA), through a similar process of industry involvement, also developed a roadmap for future mass storage requirements. Starting with these two documented visions of future mass storage requirements, the working committee identified those requirements which depend on materials or materials processing research and developed a consensus regarding investment priorities for these research activities. Several non-technical recommendations were also developed. A materials related roadmap is included at the end of this section. The NSIC and OIDA roadmaps should be referred to for a more detailed review of industry requirements.

Specific Recommendations [2, 3]

Magnetic and Optical Storage Media

Media materials, including the recording substrate, are critically important to achieving high areal recording densities (1.55 Gbytes/cm^2). Generally, base materials must have low temperature and humidity coefficients for dimensional and environmental stability.

Today's recording tapes use a polyester substrate which is available at low cost because of its high volume, non-recording applications. Promising materials for mass storage application are unlikely to become available at low cost unless additional, higher volume uses of the material are also developed.

As areal recording densities increase, each recorded bit becomes smaller, requiring increased coercivity to retain magnetization. In addition, the particle size must be reduced to reduce media noise. New small-particle magnetic media materials and corresponding coating technologies are needed. Japanese leading-edge technology in this area is demonstrated in Fuji's very thin, low noise, "dual layer" coating. In optical storage, both write-once-read-many (WORM) and erasable recording materials with high sensitivity in the blue spectral region are needed to operate with future optical recorders which achieve higher recording densities by use of shorter-wavelength sources.

Magnetic Heads

In the future, most magnetic heads will be made by thin-film fabrication techniques and will employ new, principally giant magnetoresistance (GMR), active materials. GMR materials act as sensitive reading devices by changing resistance in the presence of the very small magnetic field variations recorded on the magnetic media. Beyond GMR, a class of materials called colossal magnetoresistance materials (CMR) may provide even higher sensitivities. CMR materials are semiconductor-like oxide films.

Magnetic Head-Media Interface

The head-media interface is a critical area requiring its own special materials and coatings. Lubricants, frictional polymers, new head designs, sliders and dimensionally stable materials will become increasingly important as head-media spacing is reduced for higher data density and data rates. Future requirements may require contact recording or zero spacing.

Advanced Storage Technologies

Flash memory performance will be paced by advances in semiconductor capabilities. The consensus is that flash memories will not impact mass storage applications in the time frame within the scope of this report. Flash memory is addressed in more detail in the Microelectronics report.

Three dimensional (3D), holographic, and 2-photon memories have the potential for providing huge storage densities. The consensus of industry participants however, was that these technologies will not significantly impact mass storage products during the next decade

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[2] Specific material requirements - what, why, and when - are detailed in the accompanying Materials Roadmaps (Tables 1-4, pages 20-22).

[3] There was some concern that optical issues expressed in Table 4 concentrated on the high performance side of optical storage. In addition, there is a drive to low performance, low cost optical storage. The issues here concern high capacity substrates. For instance, there is a need for high capacity for video storage even before the full development of blue lasers. There is also a need for phase change erasable CD materials. The media creates the primary materials issues in this market segment, and issues center fundamentally on cost and volume.

which is the time-frame of this workshop.

Materials Outline

In considering materials related mass storage research needs and in developing recommendations, the breakout session utilized the following outline:

Recording Media for Higher Density Recording

1. Substrate

Tape (optical and magnetic)
Smooth
Thin/high modulus
Stable temperature and humidity coefficients
Optical Disk
Molding resins

2. Coatings

Magnetic Tape
Nanoparticle, thin coatings
High H_C and M_R
Environmentally stable
Optical
Shorter wavelength media
Phase change and magneto-optic materials

Recording Heads for Higher Density Recording and High Data Rates

1. Optical

Shorter wavelength sources
Multidiode arrays (for higher data rates)
Phase change and magneto-optic materials for erasable CD's

2. Magnetic Disk and Tape

M_R, GMR heads: improved sensitivity for reading smaller bits
High M_S materials for write heads
Low wear materials
Multichannel methods for increased data rates
High frequency pole materials, such as laminated structures

Advanced Storage Technologies

1. Flash memory

2. 3D, Holographic and 2-photon memories

Non-technical Recommendations

Funding

Promising advances in magnetic storage technology appear to offer short-term opportunities for orders of magnitude improvement in storage density. Optical storage is now growing at a fairly rapid pace; however, funding of optical recording research and development in this country is below the "critical" level required to achieve important progress. Holographic and other advanced storage technologies hold promise for increasing storage densities by orders of magnitude. Industrial participants generally felt this would occur in ten to fifteen years. This assessment leads to the conclusion that magnetic storage will remain the high capacity work horse of the industry for the next five to ten years. Consequently, the recommendation is made that, while research investments should fund the full spectrum of memory technologies, the bulk of the funding should be directed at established, low risk technologies (magnetic and optical) with the remainder going to advanced, higher risk technologies including holographic and 2-photon. A funding split of 60% magnetic, 30% optical and 10% advanced technology is suggested.

Policy

Because of the high costs of developing new mass storage substrate materials, the working committee strongly recommends that pre-competitive, magnetic and optical research be leveraged by use of industry consortia and alliances such as the NSIC and the National Media Lab (NML). In addition, alliances and consortia offer a greater chance of commercial success for new technology by virtue of their broader knowledge and skill base when compared to an individual organization. The observation was also made that, for similar reasons, university "Centers of Excellence" appear more efficient in converting research dollars into materials advances than individual academic institutions.

Infrastructure

Manufacturing processes for new materials are as important to commercial success as the materials themselves. Such process research must be supported along with materials research. New materials which are compatible with existing manufacturing processes have a decided edge in achieving commercial success over those requiring new production techniques. FeN films were cited as an example of a promising new mass storage material requiring manufacturing compatibility with current processes for successful commercial adoption.

MATERIALS ROADMAPS [4]

Table 1: Media Roadmap

WHAT	WHY	WHEN	EXAMPLE / COMMENTS
Smooth media	Improved SNR due to reduced spacing		
Substrate (thickness, mechanical stability, environmental stability)	Volumetric density, SNR (tape), Narrow tracks, multitrack recording, high TPI		PEN, PET, Aramid, PBO
Grain size reduction (hard disk and ME or sputtered tape)	Improved SNR at high densities	300 kFCI - Yr 1988 1000 kFCI - Yr 2005	Cr/CoCrX alloy, High anisotropy alloys, BaFe, ReCo/Fe alloys, CoNi tape, Array of single domain grains
Particle size reduction (particulate tape)	Improved SNR at high densities	.12 Tbyte/cm^3 - Yr 2000 .6 Tbyte/cm^3 - Yr 2010	MP, BaFe
Metal particles coating	Environmental stability		
Wear resisting overcoats	Durability of interface		Carbon, Zirconia
High moment M_R	High signal (high density recording)		
High M_Rt	High signal for low t (high density recording)		Thickness reduction without change in M_Rt
High H_C	High density recording	> 2000 Oe - Yr 1996 > 5000 Oe - Yr 2005	FeSnN
Media chemistry	Long term stability, archivability		

Underline bold print indicates area of highest priority

[4] Chart format courtesy of T. Jagielinski, Eastman Kodak Company, 3985-A Sorrento Valley Boulevard, San Diego, CA 92121-1402.

Table 2: Inductive Heads Roadmap

WHAT	WHY	WHEN	EXAMPLE / COMMENTS
High M_S pole material	Record on high Hc media, allowing high FCI & TPI	1.55 Gbytes/cm² - Yr 2000 155 Gbytes/cm² - Yr 2010	$FeXN/SiO_2$ FeXN (X = Al, Ta, Hf)
High frequency pole material	High transfer rate Write equalization		Multilayers
Substrate - wear	Long life, Adjusted to pole pieces, Differential wear		SiC, No differential wear allowed
Insulators	Wear resistant, long life, zero differential wear, reduced # of turns, higher current		Gap area and overcoat No differential wear allowed
Materials to be patterned by RIE	Simplified fabrication process Low cost		Ion milling expensive
Wear resisting overcoats	Durability of interface		Carbon, Zirconia
Metal Laminated (ML) Materials	HDTV, advanced VCR		

Underline bold print indicates area of highest priority

Table 3: Magnetic Recording Heads Roadmap

WHAT	WHY	WHEN	EXAMPLE / COMMENTS
<u>GMR, CMR materials</u>	High signal, SNR at high densities	1.55 $Gbytes/cm^2$ - Yr 2000 155 $Gbytes/cm^2$ - Yr 2010	(NiFeCo/Cu) Multilayer, NiFe/Cu/NiFe, Improve sensitivity 30x by Yr 2010, dR/R - 50-1400%
Substrate - high wear thickness - high thermal conductivity	- Long life - High I_S current - Large output	1.55 $Gbytes/cm^2$ 15.5 $Gbytes/cm^2$	SiC No differential wear allowed
Insulator material - high wear thickness - high thermal conductivity	- Long life - Improvement in output (allowed MR head to operate at high current densities)		DLC No differential wear allowed
Domain pinning materials	Single domain state stabilization		NiMn, FeMn
Environmental stability	Long life, domain stabilization		Corrosion

Table 4: Optical Roadmap

WHAT	WHY	WHEN	EXAMPLE / COMMENTS
Short wavelength lasers Blue	Higher recording densities	Yr 1998 Yr 2005	430-500 nm 340-430 nm
Short wavelength media (writable MO, phase change, stability, organic, inorganic)	High recording densities (reliability, cost)	Yr 1998	TbFeCo TbFeCo, phase change High Kerr effect
Advanced 3D storage holographic	High data ratio Volumetric storage	Yr 2000 - 2005 possible Yr 2010 - 2015 likely	
<u>Detector short wavelength</u>			

<u>Underline bold print</u> indicates area of highest priority

Module Interconnection

Introduction

Module Interconnection encompasses above-chip level fabrication, packaging, interconnection and assembly. The module interconnection industry is composed of hundreds of small, medium, and large businesses involved in all phases of the process. The module interconnection fabrication industry is over $21 billion worldwide and $5.5 billion in the U.S. The U.S. materials market that supports this industry is $1.4 billion, 60% of which is associated with laminates and 40% with consumable chemicals. The module assembly industry in the U.S. is valued at $60 billion, with the majority of materials costs coming from semiconductor components and interconnection products.

Historically, technical innovation and evolution in module interconnection has taken place within the large, captive research and manufacturing corporations. Today, however, even these organizations are conducting less R&D. Due to the predominance of small businesses in this industry, the ability of these companies to compete in the global marketplace is therefore challenged. The growing awareness that system performance that matches chip level performance depends critically on interconnect technology has led to major changes in the industry. First the Institute for Interconnecting and Packaging Electronic Circuits (IPC) has established a technology roadmapping process to help steer future research and development in the module interconnection industry and to integrate new technologies into the marketplace. Issued first in 1993, then updated in June 1995, the IPC and the module interconnection industry issued a national technology roadmap that is strongly linked to semiconductor trends and customer needs. Second, through the leadership of IPC, the Interconnection Technology Research Institute (ITRI) was established in June 1994 to provide a vehicle for collaboration to enable revolutionary innovation and solutions to future requirements in module interconnection through improvement of existing technologies and development of advanced technologies.

With the increase in Asian printed wiring board (PWB) production, the U.S. global market share in electronic materials and module interconnection has dwindled in recent years. New materials exist, though prohibitive costs and insufficient infrastructure often prevent their widespread adoption in the U.S. Inertia towards change is a key element influencing today's industry. Coordinated and integrated innovation across all aspects of module interconnection is required if timely adoption of new materials, manufacture or processes is to be realized. Overriding pressures to reduce costs for virtually all aspects of the module interconnection enterprise, be it materials, processes, fabrication, or assembly, pervades the industry. For the U.S. module interconnection industry to successfully compete in the global microelectronics market, it must build in a timely fashion the technical competencies needed to fully manage the technological innovations and requirements of upstream suppliers while delivering the required system level characteristics at a cost specified by OEM customers.

Drivers and Issues

Four primary forces are driving materials technology evolution and innovation in module interconnection. They include **price, reliability, portability** and **performance.** Table 5 (page 26) details these four forces and provides envisioned responses. Arising from these forces and responses, seven priority technical issues emerge which directly impact advanced materials in module interconnection. The specific needs associated with each technical issue are detailed in Table 6 (page 27). These issues are:

Low Dielectric Constant Materials for High Frequency Applications

The high frequency market is a growth segment for the module interconnect industry. Readily processable advanced materials using existing equipment are needed to meet cost and performance needs.

Dimensionally Stable Polymer Structures

Improved dimensional stability of polymer resins and assembled multi-component structures allows for increased circuit density and reduced manufacturing scrap, and is driven by trends in component I/O density.

Moisture Resistant Resins

Moisture resistant resins reduce processing costs, improve dimensional stability and minimize variability in dielectric constant.

Conductive Adhesives

Major materials break throughs are needed for anisotropic conductive adhesives if their widespread use in fine-pitch assembly is to be realized. Improvements are needed in bond strength, cost, availability of fine filler particles, corrosion and component registration. Major advances in the field of inherently conductive polymers like polyaniline and polypyrrole could offer useful alternatives.

Photoimageable Dielectrics and Photoresists

Utilization of photoimageable dielectrics and photoresists can reduce the cost of board fabrication, yield more environmentally benign processes and finer board lines.

Polymer Underfills

Polymer underfills help minimize the effects of CTE mismatch and improve assembly reliability. Reworkable underfills reduce costs and scrap.

Improved Solders

Lower temperature solders allow utilization of other materials presently incompatible with today's processing and reduces board stresses during assembly. Lead-free solders are needed to meet future lead use requirements. Improved solder mechanical integrity may eliminate use of chip underfills.

Cost and Business Issues

In addition, a series of cost and business issues cut across all aspects of Module Interconnection. These issues influence the ability for new materials and processes to be utilized and represent some of the most pressing challenges to the industry. The overriding pressure is to drive cost out of the products and processes. Consequently, tradeoffs for systems level enhancements are not always considered due to higher costs incurred somewhere within the food chain. This contributes to the significant inertia towards change which exists within the industry. Specific business, specification, and customer issues are detailed in Table 7 (page 27).

Recommendation

The push to increased complexity and reduced feature size is a prominent theme within Module Interconnection and throughout this report. Enhancement of current materials and development of new materials in a short time frame to enable industry to meet the requirements of increased density and reduced feature size is needed for the industry to remain competitive.

Table 5: Primary Technology Drivers and Responses in Module Interconnection

DRIVER	RESPONSE
Price - Process Step Reduction - Reduced Materials - "Green" Processes - Yield Improvements - Improved Panel Utilization	- Permanent Resists - Photo Formed Vias - Single Sheet Prepreg - Waste Recovery / Reuse - Waste Elimination - Large Panel Format - Laser Direct Write Imaging - Lead Free Solder
Reliability - Improved Materials - Improved Test - Improved Build Process - Yield Improvements	- High Performance Resins - High Ductility Copper - Latent Defect Test - Optical Test for Near Defects - Optical Registration - High Density Pad on Pad Connectors

Portability
- Thin
- Light Weight
- Miniaturization
  - reduced levels of packaging
  - double sided assembly
  - interconnect density
  - high density I/O
	- Thinner Foils
	- Thermal Vias
	- Fine Line Circuitry
	- Optical Test
	- Thin Glass Cloth (38 μm)
	- High Performance Resins
	- Photoimageable Dielectrics

Performance - Tighter Grids - Finer Lines - Smaller Holes - Improved Electrical Properties - Higher Operating Temperatures - Interconnect Density - High Density I/O - Reduced Levels of Packaging	- Thinner Foils - Full Build Electroless Plating - High Resolution Resists - Optical Test - Thin Glass Cloth (38 μm) - High Performance Resins - Photoimagable Dielectrics - Pad-on-Pad Interconnects - Direct Chip Attach
Very High Performance - Very Fine Grids - High Density Low ϵ_r Materials - Ultra High I/O - Very High Layer Count - High Density Connector - Vertical Wiring - Matched CTE Construction	- CIC or Aramid Construction - Teflon, Cyanate Ester - Integrated Flex I/O - Optical Process Registration - Pad-on-Pad Interconnects - Parallel Process - Stacked Via - Selective Lamination - Embedded Components

Table 6: Technical Issues and Needs

ISSUE	NEEDS	
	3-5 Yr	>6 Yr
Low dielectric constant materials for high frequency applications	- Low loss alternative to PTFE for >1 GHz operation - Higher T_g (>200 °C) substrates compatible with wire bonding	- Easily processed materials for 18-94 GHz operation
Dimensionally stable polymer structures	- Substrate materials meeting 100 ppm variance	- Substrate materials meeting 50 ppm variability
Moisture resistant resins	- Substrate resins with <0.5% wt moisture uptake	- Substrate resins with <0.1% wt moisture uptake
Conductive adhesives	- Improved strength and reduced cost of filled adhesives - Fine pitch conductive particles - Reduced conductive particle corrosion	- Establish robust infrastructure and training - Improved component registration - Develop inherently conductive adhesives
Photoimageable dielectrics and photoresists	- Permanent photoresists - Increased utilization of photoimageable dielectrics	- Environmentally benign materials and processes
Polymer underfills	- Reworkable resins	--
Improved solders	- Lower temperature solders	- Mechanically robust solders to eliminate need for polymer underfills

Table 7: Cost and Business Issues

ISSUES		
BUSINESS	SPECIFICATION	CUSTOMER
- Profitability of vendors - Development of domestic suppliers - Difficult to incorporate revolutionary materials - Loss of low cost materials suppliers	- Use of single ply laminates - Reduced peel strength requirement - Joint reliability testing	- Material choices driven by process and assembly, not end product requirements - Vertical partnering needed to institute changes

Materials Characterization

Introduction

Materials are the building blocks of all electronic systems, whether they are simple or complex, analog or digital, microelectronic or optoelectronic, whether they operate at RF or microwave frequencies, and whether they are intended for computation, data transfer or mass storage applications. To produce high quality low-cost reliable world class products, the attributes of the electronic materials must be measured at all stages, from starting materials through fabrication, packaging and final assembly. Characterization represents the infrastructure required to control quality in manufacturing, as well as nurture discovery and development of the beneficial properties of new materials. Major challenges are the high cost of state-of-the-art tools, the cost of maintaining in-house capabilities and the corresponding critical expertise needed to collect and interpret the data to provide quality control over all the materials used in electronic device manufacturing.

Presenter and Discussion Summary

The working committee recognized the difficulty of identifying and prioritizing the measurements for present, near-term, and long term. Figure 2 shows a history of analytical measurement techniques relative to the decline of minimum integrated circuit (IC) geometry. Each technique was considered revolutionary when first introduced. Experience has shown that from the point of introduction, each technique improves in an evolutionary fashion in response to driving forces for improved performance, i.e. smaller analytical spot, higher sensitivity and improved surface selectivity.

There is a distinction to be made in contrasting the role of materials diagnostics for low volume versus high volume production manufacturing. In low volume, such as in a flexible manufacturing situation, the process and products need to be measured continually in real time, preferably by in situ methods. For high volume manufacturing, the objective is to fine tune the process until diagnostic techniques can be eliminated altogether. It is the development phase, with high volume manufacturing as a goal, that demands the most from materials characterization.

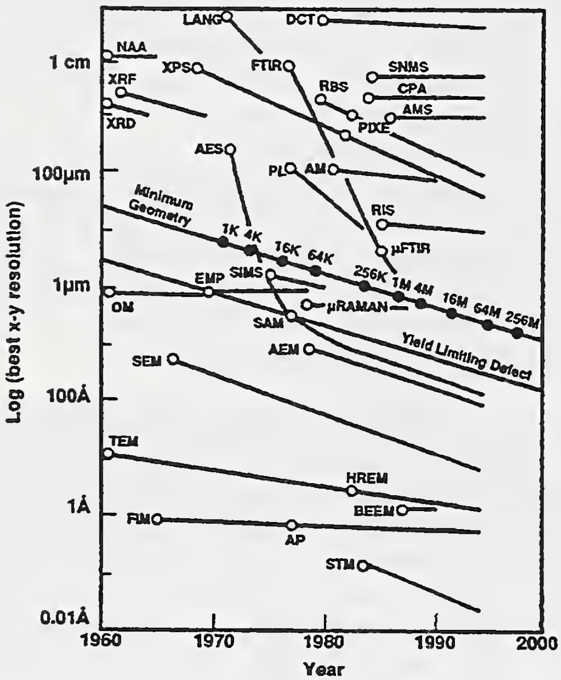
The techniques listed in Figure 2 are important to the semiconductor industry, in that each has improved and retained usefulness over the years. Continued evolution of each to higher resolution, more sensitive robust tools is needed. In an environment of limited resources, the challenge is to rank techniques against need, and define the purpose of each. Each purpose can be arranged under technology themes, which are:

(1) starting material qualification,
(2) novel materials and structures,
(3) process development,
(4) process monitoring (*in situ*),
(5) process monitoring (on-line),
(6) off-line monitoring, and
(7) failure analysis.

Starting Material Qualification

Techniques for characterization of a starting material like silicon are well-detailed in the NTRS and need not be addressed in great detail here. Others, such as III-V materials, have characterization needs for measuring dislocation density and EL2 density and distribution uniformity. Ways for these characterization tools to accommodate the next generation of 150 mm wafers have to be explored.

HISTORY OF ANALYTICAL TECHNIQUES
RELATIVE TO THE STEADY DECLINE OF MINIMUM IC GEOMETRY



AEM	Analytical electron microscopy
AES	Auger electron spectroscopy
AM	Acoustic microscopy
AMS	Accelerator mass spectroscopy
AP	Atom probe
BEEM	Ballistic electron emission microscopy
CPA	Charged particle activation analysis
DCT	Double crystal X-ray topography
EMP	Electron microprobe
FIM	Field ion microscope
FTIR	Fourier transform infrared
HREM	High resolution electron microscopy
LANG	Scanning Lang X-ray topography
NAA	Neutron activation analysis
OM	Optical microscopy
PIXE	Particle induced X-ray emission
PL	Photoluminescence spectroscopy
RIS	Resonance ionization spectroscopy
RBS	Rutherford backscattering spectroscopy
SAM	Scanning Auger microprobe
SEM	Scanning electron microscopy
SIMS	Secondary ion mass spectroscopy
SNMS	Sputtered neutral mass spectroscopy
STM	Scanning tunneling microscopy
TEM	Transmission electron microscopy
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
XRF	X-ray flourescence
µFTIR	Microspot FTIR
µRAMAN	Raman microprobe

Figure 2: History of Analytical Techniques Relative to the Steady Decline of Minimum IC Geometry (Provided by Thomas Shaffner, Texas Instruments, Box 655936, Mail Stop 147, Dallas, TX 75265).

For flat panels and storage media, measurement of substrate panel flatness both in terms of bow and surface roughness is extremely important. The characterization of deposited films on substrates for properties such as thickness, defect density, resistivity, and chromaticity is also needed. Adaptation of measurements to meet the needs of large-area substrates is also required.

Novel Materials and Structures

Characterization of the properties of novel materials and structures, particularly nanostructures, will utilize the same techniques as detailed above, with emphasis on small spot probes and atomic resolution capability.

Process Development

Means of determining the efficacy of fabrication processes need to be further developed in the areas of thickness and composition control of thin films, both two- and three-dimensional profiling of dopant concentration and distribution, three-dimensional imaging and characterization of critical dimension features, detection and characterization of particulate contamination and defects, and characterization of the properties of new dielectrics.

In Situ Process Monitoring and Control

Methods of in-process diagnosis and control of the unit fabrication processes need to be developed further. The important parameters to be monitored can be arranged in three categories:

- Substrate: including film thickness and composition, temperature, stress, and abruptness of interfaces;

- Process: including monitoring the state of the reactants (flow rates, purity, etc.), monitoring the plasma state, and detection of particle generation; and

- Equipment: monitoring of RF power, point-of-use chemical purity, and ambient hazards through implementation of environmental sensors. In addition, the methodologies for using this information to optimize the process, including CAM tools, need further development in terms of improved process and yield control models, and control schemes such as feed-back loops and feed-forward controls.

On-Line and Cleanroom Process Monitoring and Control

Advances are also needed in the inspections and measurements done between unit processes that verify the state of the product as it moves through the fabrication line. These include particle and defect detection, composition analysis, and source identification; detection of metallic and organic contamination; critical dimension measurement; film thickness measurement; confirmation of design intent for flat panels, that is, verification of the end result of a given process; overlay control; process validation; determination of implant dose; measurement of the structural properties of critical features; and development of improved pattern recognition methodologies that will enable automation of the process.

Off-Line Monitoring

Characterization and measurements done outside the process sequence include determination of implant dose; three-dimensional profiling of dopant concentration and distribution; contamination control; measurement of stress at small spots; determination of gate reliability; characterization of surface roughness; and determination of layer thickness and composition.

Failure Analysis

Techniques for failure analysis that are important now and will continue to be important in the future include cross-sectional techniques; microspot chemical and physical analysis; hot electron imaging; and three- dimensional tomography, including X-ray, acoustic, electron and ion beam techniques. These and other techniques need further development to diagnose package stress, hermeticity, and causes for delamination; and to characterize metallization failures.

Material Characterization Needs

To meet these needs, the following capabilities need to be developed or improved:

Near Term

- Fast visible light imaging detectors for III-V materials quality characterization.
- Higher sensitivity detection of organics in process fluids.
- Materials which generate low particle counts during fabrication.
- Smaller spot size ion beams.
- Wet chemical cleaning process control sensors for bath concentrations and trace contaminants.
- Electron holography for dopant profiles and magnetic materials.

Mid Term
- New x-ray sources, optics, and detectors for commercial applications.
- Spectral refractive indices for optical thin films for flat panels.
- Environmental sensors for process effluent monitoring at each appropriate process tool.

Long Term
- Higher sensitivity detection of impurities on processed substrates (flat panels, III-Vs, and Si) continuous improvement.
- Massively parallel scanning probe microscopy (SPM).
- Fast non-destructive analysis of electrical properties of semi-insulating GaAs.
- Non-destructive characterization of electrical properties, such as resistivity, of thin films.

SUMMARY AND CONCLUSIONS

The existence of the NTRS for silicon technology allowed the development of a Metrology Roadmap for the silicon industry. A similar roadmap for III-V and II-VI compounds is conspicuously absent, and if drafted, would focus attention on factors influencing economic growth in these sectors, as well as providing the necessary goals to prioritize further development and application of characterization tools. The likelihood for future revolutionary characterization breakthroughs will be enhanced by a strengthened infrastructure for the physical sciences. This can be accomplished through Federal centers of excellence in materials research, characterization, and processing, and should be done in collaboration between industry, academia, and Federal laboratories.

Research Opportunities

Introduction

A multiplicity of possible research opportunities in electronics / photonics was recognized and discussed. Beyond the specific research needs and challenges, a complicating factor in a discussion of research opportunities is: (1) the interdisciplinary nature of the challenges, requirements and nature of the research; (2) the branches of science involved; and (3) the types and objectives of the organizations carrying out the research. While specific research agendas among universities, industry, and national laboratories may not coincide, several research issues common to these three sectors were identified in electronics and photonics. First, a basic understanding of the underlying chemistry and physics principles is viewed essential. Second, with increasing sophistication of analytical tools used to examine atomic scale characteristics and to understand materials and materials processing at this level, universities may no longer have the requisite facilities and resources to comprehensively pursue all the necessary types of advanced materials processing and characterization.

A restructuring of the relationships among universities, industry, and national laboratories to better meet particular demands in the areas identified are suggested. The changing focus of industrial research makes it increasingly important that universities be able to perform the basic research needed for long term benefits to industry. To meet this challenge more effectively, interactions between university researchers, and their counterparts in industry and government laboratories, need to be strengthened, and approaches need to be developed to ensure the new knowledge generated from basic research is made available to the user in a timely manner. The process is enhanced when the long term needs of industry are regularly discussed with those conducting research. This workshop is one aspect of an ongoing process to identify critical research needs and to encourage new types of interactions between the university, national laboratory, and industrial R&D communities in electronics and photonics.

Rapid progress in many diverse fields has been, and will continue to be, based on the increasing capability and cost effectiveness of microelectronics and photonics materials, devices, and circuitry. As the limits of current materials and materials processing technology are reached, new materials and processes must take the place of the ones limiting progress. For this to occur, research to identify, characterize, and understand the fundamental limits of new materials and processes must take place.

Summary of Critical Areas

A variety of technical areas, and suggestions for improvements in the methodology used to perform the research were identified for enhanced R&D. Emphasis was given to long range research topics, beyond those already identified in roadmaps like the NTRS and NEMI, that are closely identified with potential electronic / photonic applications.

It's noted that silicon will remain the most important electronic material for the foreseeable future. However, other non-silicon electronic and photonic materials have recognized advantages and remain critically important for selected electronic or photonic applications.

Creation of an improved national infrastructure for sustained long-term research is a critical issue. Materials research needs and opportunities for major advances are considered most critical in:

- synthesis and physical properties of nanostructures;
- characterization, computation and simulation of material properties for designer materials and processes;
- heterogeneous and non-lattice-matched growth and epitaxy;
- interfaces between dissimilar materials;
- interconnects;
- non-equilibrium processing; and
- wide bandgap semiconductors.

Specific Issues and Recommendations

Specific issues in each of the critical research areas are summarized here. The focus on materials research needs and opportunities for major advances emphasizes a long-term time frame for realization of each of these recommended areas of research.

Synthesis, Processing, and Physical Properties of Nanostructured Materials

- Fundamental scattering mechanisms in confined structures.
- Optical properties of quantum-confined structures.
- Magneto-resistive materials, structures and physics.
- Coulomb blockade devices (single electron tunneling devices).
- Processing routes and equipment for nanoscale structure fabrication.
- Scaled (ultra-thin film) insulators (processing and properties).

Computation and Simulation of Materials Properties and Processes (for designer materials)

- Band structure calculations prior to synthesis.
- Simulation of processes (epitaxy, deposition, etching, implantation, metallization) and resulting chemical and physical properties.
- Simulation of process tools.
- Calculations of multilayers and interfaces.
- Basic chemical and physical properties (band offsets, effective masses).
- Defects and their interactions.
- Degradation of materials and microstructures.

Heterogeneous and Non-lattice-matched Growth and Epitaxy (including direct bandgap materials on silicon)

- Heteroepitaxy.
- Understanding point, line and planar defects, and their interactions.
- Wafer bonding and fusion.
- Lateral, selective and patterned epitaxy.
- Mesotaxy (buried epitaxial growth by ion implantation, such as for silicides).
- Interface properties (band offsets, etc.).
- 3D and non-planar structures.
- Accommodation (thin) and buffer (thick) layer strategies.
- Low defect density substrates.
- Thermodynamic and kinetic metastability.
- Initial stages of nucleation.

Interfaces Between Dissimilar Materials

- Stress (chemical, mechanical) at interfaces.
- Electromigration in metals and interfaces.
- Irreversible processes (e.g., chemical and morphological reactions at interfaces).
- Microstructural evolution (e.g., submicrometer).
- Control of electronic properties of interfaces (e.g., trap and Fermi level engineering).
- Chemical interdiffusion along/across interfaces.

Interconnects

- Low dielectric constant materials.
- Grain boundary structures.
- Optical interconnects.
- Geometrical control and stability.
- Permanent resists.

Non-equilibrium (low thermal budget) Materials Processing

- Beam (ion, electron, laser) processing and beam-solid interactions.
- Surface chemistry and physics.
- Defect engineering (e.g., delta doping, non-stoichiometric effects in compound semiconductors).
- Process tool development.
- Plasma processing.
- New precursors for low-temperature growth.
- Temperature measurements of local areas.
- Modeling of low temperature processes.

Wide Bandgap Semiconductors

- Bulk crystal growth and defect reduction.
- Heteroepitaxial deposition, graded buffer layers and compliant structures.
- Alloys and characterization.
- Abrupt compositional junctions for charge carrier confinement.
- Effect of hydrogen on n- and p-type doping and reasons.
- n- and p-type doping without post-growth processing.
- Ion implantation and dopant activation.
- Reactive ion and wet etching procedures.
- Ohmic and rectifying contacts for n- and p-type materials and characterization, reactions, effect of band offsets and current transport.
- Gate and field dielectrics - effect of heteroepitaxy on breakdown and leakage characteristics.
- Essential properties: band offsets, effective masses, cause of deep states, alloying effects on Eg, electron and hole mobilities, transport as function of temperature and doping, thermal as function of temperature, piezoelectric and non-linear optical effects.
- Surface and interface chemistry.
- Point and extended crystal defects and their effect on electrical properties .
- Modeling of various devices.
- Electron emission and application for cold cathodes.
- Fabrication and testing of simple microelectronic and optoelectronic devices.
- Double heterostructure and vertical cavity lasers.
- Non-volatile memories.
- Device packaging - especially for high temperature applications.

Other (research topics and/or materials deemed important but insufficient time for discussion at this forum)

- Amorphous semiconductors.
- Si-based electronics regarding scale-up and defect-related concerns.
- Active and passive polymer structures (electronic and optoelectronic).
- Fibers for photonics.
- Phosphor technology.
- Molecular self-assembly.

National Research Infrastructure in "Long-term Research Opportunities"

- Increased on-site interactions and staff exchange among industry, government labs and universities.
- Form and motivate team research, particularly between industry, government labs, and universities.
- Include entrepreneurial training for students.
- Increased support of universities to develop a long-term research infrastructure.
- Enhanced sharing of intellectual property while maintaining proprietary obligations.
- Increased electronic / photonic materials research by materials scientists in materials departments.
- Combine good basic science research with potential applications important to industry.
- Emphasize B.S., M.S. and Ph.D. level education.
- Recognize and promote a quality education base, and a team-oriented, interdisciplinary approach to electronic / photonic materials research.

- Delicate balance between research that has impact on industry but is not controlled too tightly by industry.

Common Elements

Some materials research issues are not necessarily specific to an application or material, and were therefore represented in several of the critical research areas. The development and understanding of processing routes and equipment were seen as a need for synthesizing nanostructure materials and for low thermal budget processing of materials. Simulation / modeling was identified as filling an important need for predicting materials and device properties, and anticipating processing requirements and effects, toward the goal of tailoring "designer" materials. Deposition techniques requiring further fundamental understanding included homo- and heteroepitaxy, along with the development of improved precursors for low-temperature processing. Also important for most devices is a better understanding of defects and their interactions; dopant distribution; surface and interfacial chemistry; and the stability of interfaces, phases, grain boundaries, microstructures, and non-planar structures. Processing techniques recognized as cross-cutting included plasma, ion, electron, and laser beam processing; and etching techniques.

Summary

A wide array of electronic / photonic materials issues, needs and opportunities for major advances in the field was identified. Since research was seen to provide the foundation for successful advancement in the application areas discussed, considerable thought was devoted to exploring ways to enhance the research climate.

The contributions of industry to research efforts in universities and national labs can not be over-emphasized. The fiscal burden of advanced processing and characterization equipment to universities is a hindrance that needs to be addressed. Interactions between university researchers and their counterparts in industry and government need to be strengthened, perhaps through regional centers, and greater staff and student exchanges. Approaches need to be developed to ensure that new knowledge generated from basic research is made available to the user community in a timely manner. Teaming arrangements that eliminate duplication of effort and resources were heavily favored. The team approach was also advocated among the basic sciences within the university that contribute to electronic/photonic materials research. A cautionary note was sounded, however, in that although applications-oriented research is favored by the funding industries, universities must retain a degree of intellectual freedom and not be overly controlled by the near-term interests of industry.

Appendix A: ABBREVIATIONS

3D	three dimensional
AAAS	American Association for the Advancement of Science
AEM	analytical electron microscopy
AES	auger electron spectroscopy
ACerS	American Ceramic Society
AlGaAs	aluminum gallium arsenide
AlN	aluminum nitride
AM	acoustic microscopy
AMS	accelerator mass spectroscopy
AP	atom probe
ARPA	Advanced Research Projects Agency
ATP	Advanced Technology Program
BaFe	Barium Ferrite
BEEM	ballistic electron emission microscopy
CAD	computer aided design
CAM	computer aided manufacturing
CCD	charge coupled device
CCIT	Committee on Civilian Industrial Technology
CD	compact disc
CMOS	complementary metal oxide semiconductor
CMR	colossal magneto-resistance
CoNi	Cobalt nickel
CPA	charged particle activation analysis
Cr/CoCrX	Chromium/cobalt chromium
CTE	coefficient of thermal expansion
DCT	double crystal x-ray topography
DLC	diamond-like carbon
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DRAM	dynamic random access memory
DSSC	Data Systems Storage Center (at Carneigie Mellon)
EIA	Electronic Industries Association
EL2	a defect in GaAs
EMP	electron microprobe
EMWG	Electronic Materials Working Group
FeMn	Iron manganese
FeN	Iron nitride
FeSnNi	Iron tin nickel
FIM	field ion microscope
FTIR	Fourier transform infrared
GaAs	gallium arsenide
GaN	gallium nitride
GMR	giant magneto-resistance
H_c	coercive field
HDTV	high density television
HREM	high resolution electron microscopy
IC	integrated circuit
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
ILD	interlayer dielectric
InP	indium phosphide
I/O	input/output
IPC	Institute for Interconnecting and Packaging Electronic Circuits
ITRI	Interconnection Technology Research Institute
JESSI	Joint European Submicron Silicon Initiative
LANG	scanning Lang x-ray topography
LED	light emitting diode
ME	metal evaporated
MatTech	Materials Technology Subcommittee
MEMS	micro-electromechanical systems
μFTIR	microspot FTIR
μRAMAN	micro-Raman microscope
MITI	Japan Ministry of International Trade and Industry
MMIC	monolithic microwave integrated circuit
ML	metal laminated
MO	magneto-optic
MP	magnetic particle
M_R	residual magnetization
M_S	saturation magnetization

NAA	neutron activation analysis
NASA	National Aeronautics and Space Administration
NCSU	North Carolina State University
NEA	negative electron affinity
NEMI	National Electronics Manufacturing Initiative
NiFeCo/Cu	Nickel iron cobalt/copper
NiFe/Cu/NiFe	Nickel iron/copper/nickel iron trilayer
NiMn	Nickel manganese
NIST	National Institute of Standards and Technology
NML	National Media Lab
NRL	Naval Research Laboratory
NSIC	National Storage Industry Consortium
NSF	National Science Foundation
NSTC	National Science and Technology Council
NTRS	National Technology Roadmap for Semiconductors
NVSM	non-volatile semiconductor memory
Oe	Oersted
OEM	Original Equipment Manufacturer
OIDA	Optoelectronics Industry Development Association
OM	optical microscopy
OSTP	Office of Science and Technology Policy
PBO	polybenzoxazole
PEN	polyethylene napthalate
PET	poly ethylene terephthalate
PIXE	particle induced x-ray emission
PL	photoluminescence spectroscopy
PWB	printed wiring board
R&D	research and development
RBS	Rutherford backscattering spectroscopy
ReCo/Fe	Rare earth cobalt/iron
RF	radio frequency
RIS	resonance ionization spectroscopy
SAM	scanning Auger microscope
SEM	scanning electron microscopy
SEMATECH	Semiconductor Manufacturing Technology
SEMI	Semiconductor Equipment and Materials International
SIA	Semiconductor Industry Association
SiC	silicon carbide
SIMS	secondary ion mass spectroscopy
SNMS	sputtered neutral mass spectroscopy
SNR	signal to noise ration
SOI	silicon on insulator
SONOS	silicon-oxide-nitride-oxide-silicon
SPM	scanning probe microscopy
SRC	Semiconductor Research Corporation
STAR	special technology area review
STM	scanning tunneling microscopy
TA	Technology Administration
TbFeCo	Terbium iron cobalt
TEM	transmission electron microscopy
T_g	glass transition temperature
TPI	tracks per inch
TR	transmit/receive
TWG	technical working group
UV	ultra-violet
VCR	video cassette recorder
VCSEL	vertical cavity surface emitting laser
VLSI	very large scale integration
WORM	write once, read many
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
XRF	X-ray fluorescence
Yr	year

Appendix B: THE ELECTRONIC MATERIALS WORKING GROUP

The EMWG is comprised of representatives from government agencies supporting programs in electronics. This includes:

- Department of Commerce (National Institute of Standards and Technology, Technology Administration)
- Department of Defense (Advanced Research Projects Agency, Naval Research Laboratory),
- Department of Energy,
- National Aeronautics and Space Administration,
- National Science Foundation, and
- Office of Science and Technology Policy.

The respective agency affiliations of the EMWG members at the time of the *Workshop on Electronic Materials* are listed below:

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The EMWG would like to especially acknowledge the assistance of the following individuals from private industry who assisted in the execution of the *Workshop on Electronic Materials* and in the preparation of this report.

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*Appendix C: REVIEWED REPORTS (References)**

Title	Reference
The National Technology Roadmap for Semiconductors	Semiconductor Industry Association, June 1994 (Draft), (Final draft approved November 1994)
Special Technology Area Review (STAR): Silicon-Germanium Devices	Report of the Department of Defense Advisory Group on Electron Devices, Office of the Under Secretary of Defense for Acquisition, June 1994 (DRAFT)
Metrology and Data for Microelectronic Packaging and Interconnection	M.A. Schen, ed., NISTIR 5520 (1994)
Optical Science and Engineering: New Directions and Opportunities in Research and Education	NSF Workshop, May 1994; NSF 95-34
Optoelectronic Technology Roadmap - Conclusions and Recommendations	Optoelectronics Industry Development Association (1994)
Materials for Future Electronics and Optoelectronics	ARPA/NSF Workshop, October 1993
IPC Technology Roadmap: The Future of the Electronic Interconnection Industry	Institute for Interconnecting and Packaging Electronic Circuits, August 1993
Photonic Materials: A Report on the Results of a Workshop August 26-27, 1992	J.A. Carpenter, Jr. and S.W. Freiman, eds., NISTIR 5299 (1994)
Epitaxy, Interfaces, Defects and Processing of Electronic and Photonic Materials	ARO/NSF Workshop, November 1991
Advanced Manufacturing Technology: The Fiscal Year 1994 Federal Program in Manufacturing Science, Engineering, and Technology	Committee on Industry and Technology, Federal Coordinating Council for Science, Engineering, and Technology, August 1993

Advanced Materials & Processing, The Fiscal Year 1994 Federal Program - A Report by the Committee on Industry and Technology To Supplement the President's Fiscal Year 1994 Budget	Federal Coordinating Council for Science, Engineering, and Technology and Office of Science and Technology Policy, July 1993
Electronics Manufacturing Technology Roadmaps and Options for Government Action	National Electronics Manufacturing Framework Committee, September 1994 (DRAFT, Version 3.0)
Special Technology Area Review (STAR): Flat Panel Displays	1994
DoD Silicon Investment Strategy	September 1993
GaN and Wide Bandgap Materials	multiple reports

* For further information regarding these reports, please contact R. Leheny, Chairman, Electronic Materials Working Group.

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Appendix E: FURTHER RECOMMENDED REPORTS

Title	Reference
Silicon Industry Report 1994	Sage Concepts, Inc. (1994)
A Series of Brief Analyses on Electronic Materials	Rose Associates, October and December 1993
Electronic Materials Reports	Rose Associates, monthly reports
Feast and Famine in Materials	Daniel Rose, Rose Associates, January 1995
National Technology Roadmap for Electronic Interconnections	Institute for Interconnecting and Packaging Electronic Circuits, June 1995
Annual Report of the Semiconductor Research Corporation	Semiconductor Research Corporation (1994)
Storage Technology Roadmaps	National Storage Industry Consortium, September 1994 (Distribution limited to NSIC member organizations and U.S. Government agencies)
The Information Storage Industry	C.D. Mee, NSIC Report, March 1994
The Digital Storage Industry	J.L. Simonds, NSIC Proposal, November 1993
Storage Technology in the Year 2000, Data Storage	C.H. Bahjorek and C.D. Mee, September 1994
Outlook for Maintaining Areal Density Growth in Magnetic Recording	Joint Intermag-MMM Conference, Albuquerque, E. Grochowshi and D.A. Thompson (1994)

Appendix F: WORKSHOP ON ELECTRONIC MATERIALS AGENDA

Tuesday, December 6, 1994

7:15 - 8:00	Continental Breakfast	
PRESENTATIONS		
8:00 - 8:15	Introduction	Bob Leheny, ARPA
8:15 - 8:45	NEMI	Jane Alexander. ARPA
8:45 - 9:10	Microelectronics	Bill Swiss, SEMATECH
9:10 - 9:35	Photonics	Kent Carey Hewlett Packard
9:35 - 10:00	RF & Microwave Electronics	Gailon Brehm Texas Instruments
10:00 - 10:25	Mass Storage	John Simonds, NSIC
10:25 - 10:50	Break	
10:50 - 11:15	Module Intercon-nects	Amar Rai IBM/Endicott
11:15 - 11:40	Materials Charac-terization	Thomas Shaffner Texas Instruments
11:40 - 12:05	Research Oppor-tunities	Bob Davis, NCSU
12:05 - 1:30	Lunch	
DISCUSSION		
1:30 - 3:00	Breakout Groups Photonics: General Session Microelectronics: Room 2201 RF & Microwave Electronics: Room 2301 Mass Storage: Room 2401 Module Interconnects: Room 2501 Materials Characterization: Room 2601 Research Opportunities: Room 2701	
3:00 - 3:30	Break	
3:30 - 5:00	Further Breakout Group Discussions	

Wednesday, December 7, 1994

7:45 - 8:30	Continental Breakfast
8:30 - 8:45	Welcome Back
SUMMARIES AND DISCUSSION	
8:45 - 9:30	Microelectronics *8:45 - 9:00 Summary Presentation* *9:00 - 9:30 Full Group Discussion*
9:30 - 10:15	Photonics *9:30 - 9:45 Summary Presentation* *9:45 - 10:15 Full Group Discussion*
10:15 - 10:45	Break
10:45 - 11:30	RF & Microwave *10:45 - 11:00 Summary Presentation* *11:00 - 11:30 Full Group Discussion*
11:30 - 12:15	Mass Storage *11:30 - 11:45 Summary Presentation* *11:45 - 12:15 Full Group Discussion*
12:15 - 1:30	Lunch
1:30 - 2:15	Module Interconnects *1:30 - 1:45 Summary Presentation* *1:45 - 2:15 Full Group Presentation*
2:15 - 3:00	Materials Characterization *2:15 - 2:30 Summary Presentation* *2:30 - 3:00 Full Group Presentation*
3:00 - 3:45	Research Opportunities *3:00 - 3:15 Summary Presentation* *3:15 - 3:45 Full Group Discussion*
3:45 - 4:30	Wrap-Up

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