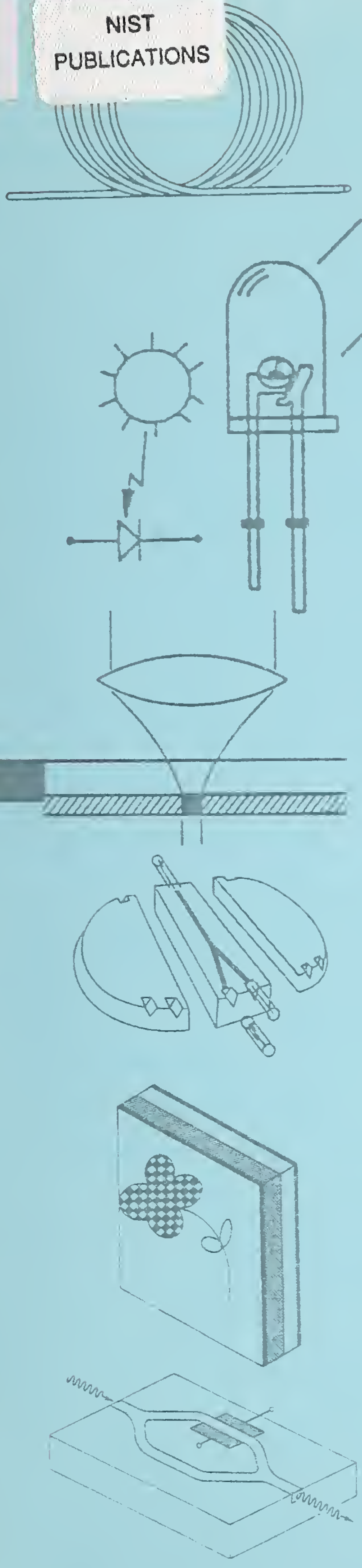

VOLUME 1: RESULTS

NISTIR 5299

Photonic Materials:
A Report on the Results of a Workshop August 26-27, 1992

**NATIONAL INSTITUTE OF
STANDARDS AND
TECHNOLOGY,
GAITHERSBURG, MARYLAND**

Co-sponsored by NIST and
the Optoelectronics Industry
Development Association

Compiled and Edited by
Joseph A. Carpenter, Jr.
Stephen W. Freiman
National Institute of
Standards and Technology

NIST
U.S. DEPARTMENT OF COMMERCE
Technology Administrartion
National Institute of
Standards and Technology

COVER ILLUSTRATION

Figures representing the six working groups of the workshop, arranged top-to bottom.

A coiled optical fiber represents the Passive Devices working group.

A photodiode (left) and a light-emitting diode (right) represent the Sources and Detectors working group.

A lens focussing a beam onto a spot on a medium represents the Storage working group.

A fiber coupler represents the Packaging working group.

An electro-optic spatial light modulator represents the Display working group.

An integrated-optical intensity modulator (or optical switch) represents the Active Devices working group.

(Note: top and bottom two figures are copied, with permission, from Fundamentals of Photonics, B.E.A. Saleh and M. C. Teich, eds., John Wiley and Sons, New York, 1991)

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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

February 1994

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Arati Prabhakar, Director

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EXECUTIVE SUMMARY

Stephen W. Freiman and Joseph A. Carpenter, Jr.,

[1]Photonics has emerged over the last ten or fifteen years to seriously challenge electronics in various applications. The world market is now about $75 billion for photonics versus $719 billion for electronics. In this early competitive stage, Japan has reaped the most benefits in large-scale manufacture of commodity items (copiers, facsimile machines, liquid crystal displays, etc.) whereas the U.S. has been a leader in technology development (especially in fiber-optic based, long-distance communications and military/avionic applications). The history of electronics strongly suggests that the accelerated competition over the next few decades will likely be paced, if not controlled, by materials technologies. Thus, the National Institute of Standards and Technology (NIST) and the Optoelectronics Industry Development Association (OIDA) sponsored this workshop with the objectives of identifying and setting priorities on materials research and development (R&D) issues relevant to photonic products expected to appear in commercial markets over the next three-fifteen years. The workshop was held August 26-27, 1992, at the NIST facility in Gaithersburg, MD.

Organized by a steering committee (see list in Program section below) of industrial, Department of Commerce (DOC), and NIST personnel, the by-invitation-only workshop was attended by 87 persons from 27 industrial firms, academia, the Defense Advanced Research Projects Agency (DARPA, now ARPA), the Strategic Defense Initiative Organization (SDIO, now the Ballistic Missile Defense Organization), the Sandia and Lawrence Livermore National Laboratories of the Department of Energy (DOE), and NIST. The Final Participants List is provided at the end of this Volume 1 (Results) and in Volume 2 (Viewgraphs) of this report.

Overview presentations identified key issues in semiconductors, polymers, and ceramics. A view of the Japanese efforts in photonics relative to that in the U.S. was also presented. Dr. Robert White, Undersecretary for Technology of the Department of Commerce, addressed the workshop on various federal government efforts aimed at promoting the R&D of U.S. industrial firms in the photonics area. Hardcopies of the presentation materials used in these overview presentations are compiled in Volume 2, available on request from the NIST editors.

Working group sessions were held in six areas: sources and detectors, display, storage, active devices (other than the four previously listed), packaging, and passive devices (other than packaging). Hardcopies of viewgraphs used in the working group sessions are also

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[1] The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. <u>Photonics Spectra</u> magazine, **27**(12), December, 1993, p. 4.

compiled in Volume 2. These six areas were selected by the steering committee as a convenient way of subdividing the topic of photonics into roughly equal parts, thus maximizing the usage of the workshop attendees. The findings of the working groups are summarized and discussed in the sections following the Introduction section of this volume of the report. The higher priority materials issues are listed below. In addition to strictly materials issues, manufacturing and measurement issues were also identified. These are shown prioritized and categorized as materials (Mat), manufacturing (Man), or measurement (Mea) issues in summary tables in each section.

Sources and Detectors

This group addressed sources and detectors used in displays, reprographics, free-space and fiber-communication systems, visible- and infrared-imaging systems, information storage, computer interconnects, information processing, and chemical monitors and sensors. The principal materials considered were III-V and II-VI compound semiconductors, but polymers for light-emitting diodes (LEDs) were also discussed. The primary materials R&D issues identified are listed in decreasing order of priority.

- Variations in substrate quality.

The creation of semiconductor sources and detectors starts with wafer substrates and growth materials. The quality of wafer substrates from the crystal suppliers varies. It is difficult to specify and guarantee the condition of the wafer materials in the region 1 to 1000 nm from the surface. Methods for the specification and new methods for the evaluation of substrates should have high priority.

- Variations in quality and stability of epitaxial source materials.

The quality of the epitaxial source materials varies. The only sure way to test a gas source used for epitaxial growth is to try it and see if positive results are obtained. This process can be very expensive. There is a need for the development of acceptable standards by which suppliers and users of the substrates and chemicals can be reliably specified and readily evaluated. In particular, better Sb, Se, and N sources for short-wavelength materials are needed.

- Variation in compositions of layers, carrier densities and contaminants in epitaxial growth.

The materials for these devices are grown using increasingly sophisticated methods, including liquid phase epitaxy (LPE), chlorine transport vapor phase epitaxy (VPE), metal organic chemical vapor deposition (MOCVD) epitaxy, molecular beam epitaxy (MBE), chemical beam epitaxy (CBE), and metal organic MBE (MOMBE). Each technique has its advantages and disadvantages and vocal proponents. There is room for improvement in the epitaxial growth processes, such as a better understanding of the growth dynamics, in-situ monitoring of species, and low temperature measurements of substrates during growth. For sophisticated structures, the growth of layers must be interrupted to perform photolithographic processing steps. Current-limiting barriers and leakage currents develop during regrowth after these processing steps. Contaminants are created at interfaces, and the interface diffusion rates are not fully understood. A better understanding of the defects created and how to avoid them is needed.

Display

The discussions of this group focussed mainly around manufacturing of active matrix liquid crystal (AMLC) and plasma forms of flat-panel displays; some attention was paid to electroluminescent (EL) flat-panel displays as well. Even though the cathode-ray tube (CRT) remains a very strong competitor for many of today's applications, it was mentioned only briefly. Frustration over the lack of a U.S. flat-panel display manufacturing infrastructure was expressed. The highest priority materials R&D issues identified are listed below, all roughly equal in importance.

- New or improved liquid crystals.

The liquid crystals used in many classes of transmissive and reflective displays are polymeric materials that must be optimized to meet several requirements. These requirements include low voltage operation, high speed, long-term chemical and thermal stability, uniform optical and dielectric properties over large areas, proper and high quality dielectric properties, correct tilt angles when the molecules are aligned, a sufficient number of aligned molecules, and compatibility with other thin-film processing steps used in the manufacture of displays. A critical challenge is to develop liquid crystals that can be aligned readily by noncontacting methods, as opposed to mechanical rubbing used today.

- Better materials and processes for thin-film transistors used in active matrix displays.

The thin-film transistors in many of today's flat-panel displays are usually hydrogenated amorphous silicon. Some thin-film transistors are made from polycrystalline silicon. A few displays use single crystalline silicon. The goals are to lower the processing temperature to be compatible with the glass substrate, increase the switching speed of the transistors, reduce the leakage currents, lower the threshold voltages, and reduce the nonuniformity in electrical characteristics of over a million pixels.

- Improved blue phosphors.

Electroluminescent (EL) displays are light-emitting displays that could outperform other display technologies for some applications. Phosphors used in displays typically are made from inorganic materials that contain strontium sulfide doped with such elements as cesium and potassium. More efficient phosphors are required to increase the number of lumens emitted per watt of input power. Full-color EL displays are not commercially available because adequate blue phosphors do not exist. In addition to increasing the efficiency of phosphors, other goals are to increase the phosphor lifetime in terms of chemical and thermal stability and to increase the brightness. The brightness of today's blue phosphors needs to be increased a factor of five to six in order to be commercially viable.

- Less expensive color filters.

Color filters are among the most critical factors in making displays "look good" and therefore are very significant in product differentiation. The cost of color filters continues to remain much higher than manufacturers had expected it to by 1993. There are three main classes of color filters - dye, pigment, and metal oxide. The metal oxides are very expensive. The goals are to develop relatively inexpensive color filters that have the characteristics of high transparency, excellent color selectivity, and long-term stability to heat, light, and chemicals.

Storage

This group addressed issues concerning laser discs, holographic memory, and persistent spectral holeburning (PSHB) mainly for use in compact disc and computer applications. Crystalline and glassy inorganic and polymeric organic materials were considered. The highest priority materials R&D issues are listed below, all roughly equal in importance.

- Active recording materials for laser-disc storage

Future short-wavelength laser-disc optical storage technology will require active recording materials with wavelength-shifted response and substantially improved properties. New magneto-optical recording materials such as novel rare-earth/transition-metal alloys and Co:Pt superlattices need to be explored. In addition, there is a need to establish a data base on existing magneto-optical thin-film materials systems and to develop improved techniques for measuring the magnetic properties. For phase-change recording materials, there is a need to investigate novel materials systems, measure thermodynamic properties of alloy systems, produce phase diagrams for candidate alloy systems, and to establish a data base.

- Polymeric materials for laser-disc substrates

Future short-wavelength laser-disc optical storage technology will also require substrates with substantially improved properties. New polymer blends will have to be developed that will allow for thinner discs with better optical properties, less adsorption of water and oxygen, less photochemical degradation, and tolerance to high temperature sputtering processes. In addition, manufacturing techniques need to be developed that reduce stress-induced birefringence, improved surface finish, and increased flatness.

- Dielectric materials for laser discs

New dielectric materials need to be investigated for use at shorter wavelengths and improved, reduced cost manufacturing techniques need to be developed for depositing thin layers, improving adhesion, and reducing thermal mismatches.

- Materials for holographic optical storage

Holographic data storage is undergoing a renaissance of interest due to recent dramatic improvements in the enabling technologies of laser sources, page composers, and detector arrays. Photorefractive recording materials are the best choice for re-writable volumetric holographic data storage, but need to be substantially improved to make this a practical technology. The existing inorganic photorefractive crystals need to be produced by new crystal growth techniques to reduce striations and other defects. Newly discovered photorefractive polymers need to be improved in terms of data-storage time and nondestructive readout, but offer the possibility of low cost, large area samples.

- Materials for blue or ultraviolet solid state diode lasers

The three main approaches for practical short-wavelength optical storage laser sources are frequency doubled near-infrared diode laser sources, diode-laser-pumped upconversion lasers, and diode lasers that emit directly in the blue or ultraviolet. The frequency doubling approach is the most mature, but is limited by the cost, fabrication difficulty, and achievable optical quality of presently available nonlinear optical crystals such as potassium niobate. Research on materials and fabrication methods for frequency doubling in optical waveguides could have substantial payoff. Upconversion laser materials need to be improved so that room temperature operation can be achieved in bulk and planar waveguide samples. The semiconductor materials systems that comprise the recently discovered short-wavelength diode laser need to be substantially improved to permit high power, continuous wave operation at room temperature.

Active Devices

The scope of this group included those components "...other than a laser or detector, which provide optical control via an external...signal." The discussions were mostly in the context of digital communications and analog information processing, the two main application arenas in which such active devices are used. The classes of materials considered included III-V compounds, inorganic crystals (especially $LiNbO_3$ single crystals), and organic polymers; the latter two were emphasized. Their most likely uses in various types of active devices were also identified. The highest priority materials R&D issues are listed below, all roughly equal in importance.

- Standard lithium niobate material.

Variability of lithium niobate from various vendors exists for impurity levels, nonlinear optical properties, and long-term optical durability. Lithium niobate standard reference materials (SRMs) and broadly adoptable material characterization methods suitable for laboratory accreditation need to be developed.

- Processes for fabricating low optical loss thin films.

Waveguide processing research is critical for producing a cost-effective fabrication technology. Fabrication methods have never been adequately addressed and are major obstacles to large-scale future usage of polymers. They are also critical issues for inorganic crystals other than lithium niobate and is a major impediment to their adoption as high-performance materials.

- Better quality, consistency, and data for starting materials and final nonlinear optical (NLO) materials.

Major issues confronting development of cost-effective III-V semiconductor optical devices are quality of materials and repeatability of processes. A complete mapping of "primary" and "secondary" performance data is needed for the more promising polymeric materials in order to spur their use. This includes establishing performance standards and material specifications.

- Less variability in processing.

Defect structures and material properties for lithium niobate and other inorganic crystals are intimately linked to processing methods in fabricating waveguide structures. III-V semiconductor synthesis and growth is not well controlled giving rise to structure variations with each preparation. Poor control of waveguide processing of organic polymers is a significant source of "parasitic" optical losses in waveguide structures.

- Cross-cutting issues common to all active materials.

Reduced manufacturing costs, improved information dissemination across disciplines, and broadened user acceptance of the technology are critical issues that will help define the future success of active device technologies, and will require a combined materials-, manufacturing-, and measurements-related research agenda.

Passive Devices

Passive devices are those which use the optical properties of materials that do not rely upon the application of an electric field. Thirteen such devices were identified, though most of the discussion centered around coupler/splitters, photo-induced Bragg diffraction gratings in fibers, and fiber amplifiers. Not strictly passive devices, amplifiers were included because it is desirable to incorporate an optical amplifier as an integral part of a passive device to compensate for optical loss in the device. The materials of primary interest were inorganic glasses and organic polymers for waveguides and fibers and organic polymers used as adhesives. The primary context of the discussions was telecommunications application, specifically Fiber in the Loop (FITL) and Fiber to the Curb (FTTC). The highest priority materials R&D issues are listed below, in roughly descending order of importance.

- Optical amplifiers for 1.3 μm wavelength.

In fiber amplifiers, dopant ions within the optical fiber (e.g., erbium) are pumped to a population-inverted excited state by a diode laser. A transmitted light pulse stimulates emission from the excited state at the same wavelength as the pulse. Erbium-doped fiber amplifiers which operate in the 1.5 μm range are now a mature technology. However, most of the fiber already installed worldwide operates in the 1.3 μm window for which current amplifiers are less efficient and less reliable. Neodymium- and praesodymium-doped glasses based upon zirconium, barium, lanthanum, aluminum, and sodium are the subject of recent research.

- Materials to reverse effects of chromatic dispersion.

The speed of light in a fiber optic varies slightly with wavelength. Over long distances, a sharp pulse of light becomes spread out or dispersed. There is a need for a material in which the speed of light has a wavelength dependence that would cause the dispersed light to become compressed.

- New glasses.

Further knowledge of how refractive indices of materials can be changed, in both polymers and inorganic glasses, is desired. Many passive devices rely upon differences in refractive index to carry out their intended function.

Packaging

As in electronics, packaging is a major part of the cost of photonic devices (as much as 75%), and can influence product performance and reliability. The packaging selected for a given application is a balance between performance, reliability and cost, with cost being the major consideration for commercial applications. Recent workshops and studies by other organizations were noted in the discussions, thus highlighting the increasing awareness of the relative importance of packaging to commercial photonic systems. Most of the discussions of this group focused on laser modules and fiber connectors; some minor references were made to packaging $LiNbO_3$ used as modulators and switches. The applications considered included long-haul telecommunications (TELECOM) and cable television (CATV), local telecommunication loops, data communications (DATACOM), and military. The highest priority materials R&D issues are listed below, in descending order of importance.

- Better understanding and quantification of the behaviors of alignment materials during the fixation process, subsequent testing, and over the lifetime of the product.

The major difference between photonic and electronic systems is that photonic systems require about an order of magnitude tighter dimensional tolerances in the alignment of fibers or waveguides with the lasers or waveguides on the modules compared to alignment of electrical wires with bond pads. This is especially true for single-mode fibers. The major materials issues involve the behaviors of the materials used in permanently fixing the alignments. The three main methods used are soldering, laser welding, and adhesive bonding; soldering is the traditional method, laser welding is considered by many to be the preferred method, and adhesive bonding would be preferred (because of cost and simplicity) if it could achieve the stability of laser welding. More needs to be known about the behaviors of the materials (e.g., distortion, creep, relaxation) during the fixation process, during subsequent testing, and over the lifetime of the product. Coupling efficiency was also discussed. The more important aspect is that the coupling be as stable as possible in efficiency and noise. Studies of ways of achieving such stability at lowest cost were suggested.

- Better encapsulant materials.

The active devices in photonic devices are composed of materials that are as or more sensitive to environmental degradation than those in electronic devices, so photonic circuits are almost always sealed in expensive hermetic enclosures. New "passivating materials" and techniques for applying them are needed to either complement the protective capability missing in less expensive enclosures or provide all the protection needed thus eliminating the enclosure entirely. There was discussion about the longing for an ideal material (termed the "holy glue" in analogy to the Arthurian quest for perfection) that could provide an optimal set of passivation, refractive index-coupling, low thermal expansion, high thermal conductivity and other important properties. Improvements are especially needed to lower the cost and increase the reliability of single and array optical feed-thrus of the enclosures.

Conclusion

Important materials (as well as manufacturing and measurement) R&D issues were identified for each of the technology areas explored in the workshop discussions. The participants agreed on the value of workshops of this type in which representatives from various segments of the photonics community could openly discuss industrial needs. Finally, overall interpretation of the needs expressed by the working groups is that for COMMERCIAL applications the major materials R&D issues of importance over the next three to fifteen years will be those associated with reductions in the engineering and manufacturing COSTS of the products. It is envisioned that the process of identifying and setting priorities on materials R&D needs, such as occurred in this workshop, will continue in the future.

Postscript

In the spring and summer of 1993, the OIDA held separate workshops on broad research and development in the technological areas of displays, switching and computing, hardcopy, optical storage, and optical communications. The initial results were presented at an OIDA-sponsored meeting on October 21-22, 1993, in Alexandria, VA, at which OIDA indicated intent to publish the results of their workshops sometime in 1994. Contact John Day (see Final Participants List) for more information.

INTRODUCTION

John Day, Strategies Unlimited and OIDA

Joseph A. Carpenter, Jr. and Stephen W. Freiman, NIST

The development of the laser diode in the 1970's, advances in glass science, and the development of optical storage media proved to be the enabling technologies that ushered in the modern photonics industry. These developments bridged the gap between the world of the electron and the world of the photon and opened applications for photonics, first in optical communications and second in optical storage. Today, cables of glass fiber span our continents and bridge our oceans, compact disc (CD) players are in our homes and cars, and laser printers adorn our offices. New battery operated lap-top computers only exist because of flat-panel photonic display technology.

Over the past decade, photonics has begun to perform selected functions which were traditionally performed only by electronics, functions where speed, attenuation, resolution, or electromagnetic interference (EMI) have limited the performance of the electronics. As the knowledge of photonics has spread, market applications have grown to a level in excess of ten percent of all the electronic systems. In 1993, worldwide sales of products enabled by photonics technology will reach $75 billion, compared to $719 billion for all electronics systems. With advances that appear highly probable, photonic systems should account for 25 percent of all electronics systems after the next two decades. The OIDA has forecast that by 2013, systems enabled by photonics will reach $463 billion, compared to all-electronic systems of $1,730 billion.

In the 1980's Japan proved the world leader in high-volume manufacture of photonic components and systems. While a number of major technical developments were produced in North America, especially in optical communications, Japan reaped the benefit of volume manufacture in consumer and office products. For the future, photonics will become an even more critical technology for any industrial society. Photonics-based components today account for almost forty percent of the retail price of certain computer products. Without a competitive industry, the U.S. will be at a severe strategic disadvantage in world markets.

Future developments in photonics are highly dependent upon the improvement of fundamental materials technology. To enable the U.S. to participate in this competitive environment, NIST and the OIDA jointly sponsored this workshop. The objectives of this workshop were to identify the critical material issues and set priorities on materials R&D for photonics over the coming three to fifteen years. This workshop was another element of the OIDA's continuing program to regain competitiveness in manufacturing for North America.

Organized by a steering committee (see list at end of Program section below) of industrial, Department of Commerce (DOC), and NIST personnel, the by-invitation-only workshop was attended by 87 persons from 27 industrial firms, academia, the Defense Advanced Research Projects Agency (DARPA, now ARPA), the Strategic Defense Initiative Organization (SDIO, now the Ballistic Missile Defense Organization), the Sandia and Lawrence Livermore National Laboratories of the Department of Energy (DOE), and NIST. The Final Participants List is provided at the end of this Volume 1 (Results) as well in Volume 2 (Viewgraphs) of this report.

Overview presentations identified key issues in semiconductors, polymers, and ceramics. A view of the Japanese efforts in photonics relative to that in the U.S. was also presented. Dr. Robert White, Undersecretary for Technology of the Department of Commerce, addressed the workshop on various federal government efforts aimed at promoting the R&D of U.S. industrial firms in the photonics area. Hardcopies of materials used in these overview presentations are compiled in Volume 2, available on request to the NIST editors.

Working group sessions were held in six areas: sources and detectors, display, storage, active devices (other than the four previously listed), packaging, and passive devices (other than packaging). Hardcopies of viewgraphs used in the working group sessions are also compiled in Volume 2. These six areas were selected by the steering committee as a convenient way of subdividing the topic of photonics into roughly equal parts, thus maximizing the usage of the workshop attendees. The following general questions, which the steering committee suggested, were addressed by each of the working groups.

1. What are the most important applications? For example, long-distance telecommunications, automotive, aerospace, computers, copiers, etc.

2. For these applications, what are the major materials R&D issues? For example, lack of enabling materials, lack of data on alternative materials, lack of suitable processing methods, high cost?

3. At what R&D stages should these issues be investigated? For example, fundamental research, exploratory research, prototype development, process development, process refinement (a la SEMATECH)?

4. Of these issues, which are the most important (priorities)? Why?

5. How should these issues be addressed? For example, federal funding, industrially funded consortia, or some combination?

The responses of the working groups are summarized and discussed in the following sections of this volume. In addition to strictly materials issues, manufacturing and metrology issues were also identified. These issues are shown prioritized and categorized as materials (Mat), manufacturing (Man), or metrology (Mea) issues in summary tables in each section. Hardcopies of the presentation materials used in the working group sections are also compiled in Volume 2, available on request to the NIST editors.

SOURCES AND DETECTORS

Robert Phelan, NIST

Participants:

Robert Leheny, Chairman	Bellcore
Robert Phelan, Reporter	NIST
William Ahlgren	Hughes, Santa Barbara Research Center
Nadav Bar-Chaim	Ortel
Herb Cox	Bellcore
Jan Hall	NIST
Kurt Linden	Spire
Jim McNeely	AstroPower
Ron Moon	Hewlett-Packard Labs
Tom O'Neill	Bandgap Technology
Steve Palfrey	David Sarnoff Research Center
Wolfgang Stutius	Polaroid
Charles Walker	3M Labs

Several others attending the sessions contributed significantly to the discussions.

General Comments

This working group began with a session during which invited speakers gave presentations. Eleven talks related up-to-date views of the state-of-the-art for each presenter's field of activity. For the first session, Bob Leheny requested that each speaker limit his talk to answering two questions: 1) what is the state-of-the-art for the applications he is working on and 2) what material issues limit the state-of-the-art? In the following sessions two other questions were to be addressed: 3) how can NIST help and 4) what are the priorities?

The presentations were much more heavily weighted toward the discussion of sources than detectors, but it was concluded that many of the materials problems related to sources were of similar concern for detectors. Most of the discussions concentrated on the shorter wavelength semiconductor light-emitting diodes and lasers, but longer wavelength sources, silicon solar cells and detector arrays for infrared imaging were discussed. The group covered both device-specific issues and generic material issues and concluded with recommendations of several areas where NIST could contribute.

State-of-the-Art Sources and Applications

The light sources discussed were light-emitting diodes (LEDs) and laser diodes (LDs). There are no other devices that are as convenient, reliable and efficient in converting electricity into light. The development of LEDs and LDs began with the invention of homojunction devices made from III-V compound semiconductors that emitted invisible, infrared light. The initial devices required cryogenic temperatures to operate. In the first few years, devices that operated from the far-infrared to the red end of the visible spectrum were demonstrated. There was early speculation that, with the development of the proper wavelength emitters, these devices could replace all light bulbs leading to considerable savings in energy. The first demonstration of the practical uses for these devices was for free-space optical communications. Over the last 30 years there has been a continuous effort toward the development of new LEDs and LDs that are visibly brighter, put out more optical power, are more efficient, and operate at additional wavelengths at higher temperatures for an expanding number of applications. The elevated temperature operation has come from the development of sophisticated structures that more closely confine the electrical carriers and the light inside the devices. These structures have required increasingly more sophisticated growth and device-processing equipment. Most of the progress has been done with III-V semiconductor materials, but recent demonstrations of laser emission in the blue-green part of the spectrum from II-VI semiconductors has added excitement to the development of these materials. There is some promise that polymers and other semiconductor materials may produce efficient visible light sources.

The III-V compounds of InGaAsP are used to make room temperature LDs that emit in the infrared at 1.3 and 1.55 μm for use in optical fiber communications. These devices contain ultra-thin, "quantum well", active layers to confine the injected electrons and holes in narrowly defined spaces and energy levels. They incorporate surrounding optically confining layers for the light. These two features allow for low operating currents and room-temperature operation. Gratings within the devices, called distributed Bragg reflectors, are used to stabilize the operating wavelengths. These LDs are designed for high-speed modulation, for long- and short-distance communications. They are also designed for the high linearity and the high dynamic range required for cable television applications.

Heterojunction AlGaAs/GaAs LEDs are used for red-emitting displays and efficient near-infrared optical couplers. Quantum-well AlGaAs LDs are used for recording and reading on optical discs and for printing systems. These devices and high power InGaAs LDs are used to optically pump other lasers that, through upconversion, create blue-green light. They are used to optically pump fiber amplifiers for optical communications.

At present, the III-V compounds of AlGaInP on GaAs substrates are the materials of choice for bright, red, yellow and green LEDs for displays. These devices are double heterojunction devices grown by MOCVD. It is believed that the internal efficiencies for the red and yellow devices still have potential to be improved by a factor of two to three. The green devices, although much brighter than previously developed green LEDs, may be improved by a factor greater than five. These devices exhibit lower efficiencies than expected from present theoretical understandings.

For full-color displays and higher density optical recording, blue light sources are needed. At present, commercially available blue light sources are made from SiC or GaN. These blue light sources, are considerably less efficient than the longer wavelength devices. SiC, involving an indirect electron-hole recombination, has less of a chance for becoming a bright blue light source than direct AlGaN compounds.

An alternative to the III-V direct-gap semiconductors are the direct-gap II-VI semiconductor materials. The narrow-gap, infrared-emitting, II-VIs were made into lasers early on. Although optical and electron beam pumping of wide-bandgap II-VI semiconductors to demonstrate visible laser action was accomplished over twenty-five years ago, it has only been within the last two years that efficient p-n junction devices have been demonstrated. The problem has been the development of a good p-type dopant. This accomplishment was first demonstrated by researchers at 3M, and laser emission in the blue-green region has now been demonstrated at eight laboratories. At present, II-VI continuous laser emission has been demonstrated at cryogenic temperatures and pulsed operation at room temperature, but only with very short lifetimes. There are many questions to be answered and a wide range of research opportunities to be pursued to make wide-bandgap II-VIs commercially viable devices.

From the beginning, to obtain precisely aligned mirrors for optical feedback required for LDs, cleaved crystal facets have been used. The cleaving operation has limitations related to device yield. There have been several efforts to develop alternatives to the cleaved mirrors that would allow for the processing of large arrays with greater reliability at less cost. One alternative has been to create gratings within the junction plane of the diodes that act as mirrors. Another has been to create the mirrors by dry chemical etching processes. Both these techniques have been pursued to redirect laser radiation traveling in the plane of the semiconductor wafers into vertically emitted light, perpendicular to the junction plane. These surface emitters have resulted in dense, high-power LD arrays. A third technique pursued, to reliably create arrays of surface emitters, has been to grow alternating layers of high and low dielectric constant materials below and above the light-emitting semiconductor junctions that act as very efficient mirrors. With these devices, the stimulated emission is both generated and emitted in the direction perpendicular to the junction plane and the wafer. These "vertical cavity surface emitting lasers" (VCSELs) have recently been made available in 256 element arrays with 3 mW outputs per device. Individually addressable arrays of LDs are likely to be used for displays, information processing, wavelength division multiplexed communications, directed beams for free-space communications, and optical interconnects.

From the beginning, there have been attempts to make silicon LEDs and LDs. It is well recognized that being able to combine electrical and optical components using the most used electronic device material, silicon, would be very advantageous. But, there are basic physics reasons (the same as for SiC) that involve the electronic band structure, why pure crystalline silicon cannot work as an efficient LED. In spite of this fact, recent demonstrations that modified silicon materials can emit visible radiation have encouraged additional research and spawned special meetings devoted to this area. To date, these silicon emitters are still very inefficient.

Visible-emitting polymeric LEDs have been demonstrated with light outputs that are comparable with the early III-V LEDs, but the polymeric devices also have the very short lifetime problem. Again, this is an area of active research.

A factor in the determination of priorities for photonic materials research and development is the commercial volume of devices. A discussion of the present volume of production of LEDs and LDs led to an estimate for LEDs of 64,500 square centimeters (10,000 square inches) of III-V material substrates per month, which corresponds approximately to 5,000 wafers per month. The volume of LDs for compact discs (CDs) is about 1/1000 that of LEDs. The volume for LDs for telecommunications is about 1/1000 that of CDs. Yield limitations for LDs reduce the output of these devices by factors of 10 to 100. Comparing LEDs and LDs, the present production and use is clearly dominated by LEDs.

State-of-the-Art for Detectors and Applications

Detectors are used for solar energy conversion, optical imaging, optical signal receivers, and optical couplers. As noted earlier, the discussions on detectors at this particular meeting were small due to the much greater interests and involvements of the participants in the areas of sources.

The greatest volume of detectors is for solar energy conversion. These detectors are primarily silicon solar cells. There is a continuing effort to create more efficient and less expensive solar cells out of silicon and other materials. For satellite applications, ultralight and radiation-hard solar cells are important. For specialized applications, AlGaAs detectors over silicon solar cells are used to add 66% to the power.

Arrays of silicon detectors are the most prominent devices for imaging systems such as video cameras. Ge and InGaAs detectors are used for 1.3 and 1.55 μm optical communication receivers. For military and civilian infrared imaging systems, HgCdTe detector arrays are prominent. Satellite, earth-imaging systems to monitor the environment use HgCdTe arrays. Infrared imaging systems are used as aids in fire fighting. Infrared detectors are important for chemical sensing and monitoring systems such as for measuring auto emissions and for intrusion alarms.

Material Issues

Each device and material has its specific issues, but, for this review, only the generic ones are related.

The creation of semiconductor sources and detectors starts with wafer substrates and growth materials. The quality of wafer substrates from the crystal suppliers varies. It is difficult to specify and guarantee the surface quality of the wafer materials in the region 1 to 1000 nm from the surface. The quality of the epitaxial source materials also varies. The only sure way to test a gas source used for epitaxial growth is to try it and see if positive results are obtained. This process can be very expensive. There is a need for the development of acceptable standards by which suppliers and users of the substrates and chemicals can be reliably specified and readily evaluated.

The materials for these devices are grown using increasingly sophisticated methods. Liquid phase epitaxy (LPE) was developed early for creating lasers that would operate at room temperature. This technique is difficult to scale up to large area wafers. Chlorine transport vapor phase epitaxy (VPE) and metal organic chemical vapor deposition (MOCVD) epitaxy are used to cover larger area wafers with needed crystals. Molecular beam epitaxy (MBE) allows for atomic layer monitoring of the crystal growths but at much lower growth rates. Chemical beam epitaxy (CBE) or gas source (metal organic) MBE (MOMBE) allow for faster growth rates than MBE, while maintaining the atomic layer monitoring capability. In addition, CBE wastes less source materials than the MOCVD process. Each of these growth techniques has its advantages and disadvantages and vocal proponents.

Common to most of these growth processes is the fact that there are toxic chemicals involved. One wants to use the minimum amount of these chemicals. More reliable processes could lower the wastes and reduce the costs. There is room for improvement in the epitaxial growth processes, such as a better understanding of the growth dynamics, in-situ monitoring of species, and low-temperature measurements of substrates during growth. For sophisticated structures, the growth of layers must be interrupted to perform photolithographic processing steps. Current-limiting barriers and leakage currents develop during regrowth after these processing steps. Contaminants are created at interfaces, and the interfacial diffusion rates are not fully understood. A better understanding of the defects created and how to avoid them is needed. The peripheral equipment required and efforts to assure the operation of safe systems can be very costly. The decision to use one material for a source or detector over another may be made on the basis of the safety of the chemicals involved and the production methods required.

Several processing steps beyond the epitaxial growth of the semiconductors could be improved. The quality of dielectrics could also be improved. Dielectrics contain residual stresses that limit their adhesion to substrates and one another. There are problems with pinholes and dielectric losses. The relations of etching to damage are not fully understood.

Potential Contributions to What NIST Could Do and Priorities

The working group concluded that NIST could provide standard reference materials, measurement methods, modeling, and guidance for practical, safer alternatives in the production of materials.

Methods for the specification and new methods for the evaluation of substrates and source materials should have high priority. Testing methods to establish the quality of source materials and epitaxial layers should be developed. Means for evaluating the various types (chemical, mechanical, radiative) of surface damage in the region 1 nm to 1 μm from the surface could be developed. Standards for photoluminescence, secondary ion mass spectroscopy (SIMS), and Polaron measurements could be developed to support this effort to characterize substrates.

The development of practical techniques to improve the material growth processes applicable to making real devices will contribute to the advancement of the technology, promote higher yields and lead to less toxic material wastes. The need for in-situ measurements to be used in the various growth methods was repeatedly mentioned. Such measurements should be researched and developed. Modeling of the growth processes including selective area growth will have to be pursued to support this effort. A mathematical model of large MOCVD reactors was requested. The dynamics of interfaces needs more understanding. Alternative material sources that are practical and safe for growing epitaxial layers could be investigated, documented, and promoted. The research to develop and evaluate these techniques can be very costly for a single company and is a natural pursuit for a national laboratory.

The design of more efficient structures requires data on material properties. Optical and electrical properties of quantum well materials could be determined and published. There are still questions about the basic physics and band structures of materials. A correlation between measurement methods to evaluate structures could be researched and documented.

A central lab facility to develop testing methods and make the methods available for evaluating material quality could be established.

A summary of the above mentioned issues on sources and detectors is given in Table 1, listed in decreasing order of priority.

TABLE 1
Summary of Issues Identified for
SOURCES AND DETECTORS

Issues in approximate order of descending priority	Mat*	Man	Mea
Substrates Variation in quality of the substrates in the region 1 to 1000 nm of the surface requires new processing to eliminate the variation and evaluation procedures to establish the quality. Means for determining surface conditions suitable for epitaxial deposition are needed. Standards would be useful.	X		X
Epitaxial source materials To eliminate variation in quality and stability of source materials from suppliers, new standards and supporting evaluation procedures are needed. In particular, better Sb, Se, and N sources for short-wavelength materials are needed.	X	X	X
Epitaxial growth Variations in compositions of layers, carrier densities, and contaminants should be addressed by the development of improved models of the growth processes, in-situ measurements of chemical species, and in-situ particulate monitoring in the growth chamber. The elimination of high contact resistances that arise during regrowth will also require improved models and in-situ measurements. Better control of layer thicknesses is needed; one solution is the development of in-situ methods to measure deposition rates and thicknesses.	X	X	X
Processing Better understanding of dielectrics is needed to control strain, pin-holes, adhesion, dielectric loss, and masking of small features. Improvements in etching, understanding the resulting damage, and control of large area gratings are needed. Understanding the properties of metals is needed in order to assure low contact resistances and to reduce or eliminate unwanted barriers.	X	X	
Material characterization Data for optical and electrical properties of materials are lacking preventing the use of optimum design procedures. Measurements need to be made and an expanded data base should be created. Material standards for photoluminescence, SIMS, and Polaron measurements are needed. Correlations between measurement techniques need to be made and documented.	X		X
Basic theory Better understanding of the basic physics of material band structures and what makes a good dopant is needed.	X		X
Measurement support The purchase of testing equipment and the support of expertise to evaluate measurements is expensive for individual companies. A central lab facility for such measurements could be a solution.			X
Safety and pollution Many of the chemicals used are highly toxic. Improved manufacturing techniques yielding less wastes and alternative, less toxic source materials are needed. Improved monitoring techniques would be useful.	X	X	X

*Mat, Man, and Mea are abbreviations for Materials, Manufacturing, and Measurement, respectively.

DISPLAY

Herbert Bennett, NIST

Participants

Malcolm Thompson, Chairman	Xerox
Herbert Bennett, Reporter	NIST
John Batey	IBM
John Day	Strategies Unlimited and OIDA
Roland Haitz	Hewlett-Packard
Freddy Khoury	NIST
Tom Long	American Display Consortium (ADC)
David Myers	Sandia National Labs
Ross Pollack	Plasmaco and ADC

Introduction

Displays are becoming one of the more expensive components of systems and the product differentiator in purchasing decisions. The display is the interface between machines and man. The drivers, buffers, memories, and decoders that are part of the display will only be secondary considerations. Most parts of a display system are shrinking in size except the display itself because that depends on the resolution of the eye, which is a constant.

Because the manufacturing of flat-panel displays requires considerable resources, most manufacturers choose not to make displays by themselves. A well integrated infrastructure is required for the successful mass production of flat-panel displays. Japan has a strong, vertically integrated infrastructure to support its flat-panel display industry; however, the U.S. does not. Developing an appropriate domestic infrastructure is an important step in overcoming the technical challenges discussed below. These technical challenges are faced by all makers of displays, not just those in the U.S. One way to assist the infrastructure that is missing in the U.S. is to have standards and agreed-upon specifications. These should increase the incentives for domestic suppliers and manufacturers by enabling more stable and larger markets.

As flat-panel displays become a commodity-like (though perhaps expensive) component, on-shore manufacturing will be required in order to avoid the shipping costs that are expected to average about thirty percent of the cost of large displays. The larger displays will be even more expensive to ship from off-shore places than the smaller displays. The major question, that can not be answered today, is whether the U.S. or Japan will produce the flat-panel displays used in the U.S., as is the situation today for most cathode-ray tubes (CRTs). (Only the larger CRTs are produced in the U.S.)

Most of the measurements and materials issues on which this working group deliberated are related to lowering the cost of flat-panel displays by increasing yield and to increasing performance by adding greater functionality to the display itself.

When discussing the measurement and materials issues for flat-panel displays, it is essential to consider the three aspects or dimensions associated with displays. These are the uses of the displays, the display technologies, and the manufacturing processes, each of which is discussed below. These subsections do not contain any background information of the type found in the technical literature or presented at technical conferences.

Most of this working group's deliberations concerned manufacturing processes for primarily active matrix liquid crystal, plasma, and electroluminescent displays. The focus was on flat-panel displays other than cathode-ray tubes. This weighing of time devoted to the various topics reflected the interests and experiences of those who attended the working group sessions.

Uses of displays:

Displays may be grouped according to three typical, general-size categories, and within each size category there are numerous uses of displays.

- Small (about 4 cm) displays are used in video projection, viewfinders in cameras, heads-up presentation of data (e.g., airplane pilots), cellular telephones, consumer electronics, appliances, automobiles, and the like.
- Medium (about 40 cm) displays are used in personal computers, multi-media interactive systems, video-telephones, engineering workstations, and the like.
- Large (about 100 cm) displays are used in high-definition television (HDTV) systems for direct viewing, entertainment, advertising, and the like.

Display technologies:

There are many display technologies. The advantages and disadvantages of each were not discussed in any detail. Most of the world's resources for developing new display technologies are devoted to active matrix liquid crystal displays (AMLCDs). However, there are several other technologies that have the potential to compete with AMLCDs in the future.

These other technologies include other (than AMLCDS) liquid-crystal displays (LCDs), plasma displays (PDs), plasma-addressed liquid-crystal displays (PALCDs), electroluminescent displays (ELDs), ferroelectric LCDs (FELCDs), field emission displays (FEDs), reflective mode AMLCDs, light-emitting diode displays, micro-machined mirror displays, and laser or lamp projection displays. Even though the cathode-ray tube remains a very strong competitor for many of today's applications, it was mentioned only briefly by the working group as the issues are well known.

Manufacturing processes for displays:

There are measurement and materials issues that are associated with each of the processing steps for the several technologies listed above. Some of these issues, such as inspection and phosphors, pertain to many of the above technologies. Other issues, such as measurements for alignment layers, apply to a smaller number of display technologies. The major processing concerns or technical challenges were discussed first by the working group without regard to ranking them according to barriers for making reliable and high quality displays. During these discussions the emphasis was on generic issues applicable to many display technologies.

After these discussions, the working group considered the materials and processing issues related to specific display technologies. It arranged the major challenges into highest, medium, and lower priorities for the display technologies of AMLCDs, plasma, and electroluminescent displays. Even if there had been enough time, the composition of the working group was such that it would not have been appropriate to discuss the remaining display technologies. These rankings are given in Tables 2 to 4, and are from the perspective of those who want to make competitive displays, that is, an industrial perspective. The items marked by an x denote primary area of importance, whereas those designated by an (x) in these tables denote a secondary area of impact. The highest and medium priority-challenges are shown in Tables 5 to 7. Users of displays, such as those who would include them in multi-media systems, might suggest different rankings of the same set of technical challenges.

Substrates

The inspection of incoming substrates and of substrates before and after key processing steps is essential. The inspection methods must be sensitive to particulates and other defects that are less than 1 μm in size over large areas with dimensions in many cases up to about 100 cm. Even though the pixel pitch in displays will usually be more than 10 μm, defects less than a micrometer may short-out or otherwise degrade the transistors used to control the pixels. Most inspection methods for flat-panel displays are derived from those for processing silicon integrated circuits and frequently are based on specular reflection. Specular reflection works best when the optical properties of the defects differ substantially from the background. But, this is not the case for flat-panel displays in which many of the layers and some particles or defects are all transparent. The inspection methods must detect both dielectric-transparent particles and metallic-reflecting particles. Even the packaging used for shipping the substrates (which are usually glass) to the manufacturer is an issue. Often the packing materials degrade the surface of the glass, and in some cases chemically etch the surface. Flatness and smoothness of substrates needs to be controlled to about 6 μm plus or minus 0.1 μm over short distances on the order of hundreds of millimeters to a few centimeters (the critical short-range distance for maintaining this tolerance depending on the display technology). Short-range variations are more critical than long-range variations for most display technologies. The tolerances for long-range distances across the substrates are much less demanding. They are perhaps about 20 μm for some display technologies. Tools for performing these measurements, specifications, and standards would greatly assist the making of displays. Today, standards are almost nonexistent, and the few that exist are not followed in many instances. The glass-substrate suppliers and flat-panel display manufacturers (users) should decide what these specifications should be, what the critical long-range and short-range distances for each display technology are, and what the measurement tools should be. The working group felt this was an area in which NIST could possibly help. Substrate resistivity is another critical parameter. It must be large enough so that leakage currents do not degrade performance. New tools are needed for pattern recognition and to locate opens or shorts in conducting regions and defects in insulating regions. Cleaning the glass substrates is very significant. Improved ways to clean the substrates and their coatings are needed for each processing step. Chemical vapor deposition methods and rubbing alignment layers rank very high in producing damaging particles. Also, techniques are needed for removing the built-up charge on substrates without producing particulates.

Coatings and Alignment Layers

The makers of flat-panel displays need better techniques for measuring thicknesses and resistivities of coatings. Depending on the display technology and processing step, thicknesses vary from a few tens of nanometers to several micrometers. Most display technologies have layer thicknesses from 50 nm to 1 mm, whereas plasma displays have many layers that are several micrometers. This industry would welcome ways to measure film thicknesses in the "green" state before additional processing occurs. Again, the working group felt this was an area in which NIST could work with industry to develop such methods. They also need more efficient techniques for depositing layers that do not waste these expensive and, in some cases, environmentally difficult-to-dispose-of coating materials. Ways to determine whether the coatings went on according to specifications would avoid further processing of defective substrates. One of the greatest challenges in coatings is to check the patterns of the transparent conducting layers of such materials as indium tin oxide (ITO). For example, contrast enhancers for inspecting ITO that would be removed after inspection and without lowering yield due to contamination of later processes, would greatly benefit this industry.

The alignment layer for the liquid crystal is critical in determining display performance such as viewing angle and contrast. Most manufacturers produce the essential alignment layer by a polyamide layer that is about 100 nm thick in such a way that when the liquid crystal (LC) comes in contact with this layer, the molecules in the LC are properly tilted for optimum display performance. The measurements for and the physical understanding of this key step are not based upon well established principles. They tend to be based on highly empirical recipes that have an aura of magic about them. For example, manufacturers do not know the spacing between ridges in the polyamide layer, the cross-sectional shapes, the irregularities, and the variations in such parameters across the surface. Because rubbing the alignment layers is one of the processing steps that produces damaging particles and defects, more resources should be devoted to devising alternatives to rubbing. One artifact in LCDs is image sticking, i.e., the pixel takes too long to change its state. It is thought to be related to the application of the alignment layer. But, ways to determine whether the alignment layer meets specifications are essentially nonexistent. Usually, the display is completed, but then it is too late to do anything if this critical layer turns out to have been defective. Cleaner alternatives to rubbing must be developed. Candidate methods might be oblique evaporation, ion-beam modification, or the use of Langmuir-Blodgett films. The LCD and its alignment films must have very high resistance to prevent leakage currents and thereby to hold voltages across each pixel cell.

The metrology of the alignment layer is very closely tied to the application for which the panel is designed. The alignment layer determines many of the attributes on which decisions to purchase the display will be based. For example, alignment greatly influences the viewing angle, the speed of the display, and its chromaticity. It is as critical to performance of LCDs as silicon and silicon oxide are critical to the performance of integrated circuits.

Color Filters

The cost for color filters is not dropping as rapidly as flat-panel display producers thought it would. Instead of the projected 1992 cost of about $40 per display, the cost still remains relatively high at $100 to $200 per display. Putting down color stripes and etching away unwanted portions is very expensive. Perhaps today's methods could be replaced by high quality printing processes. The optical properties of these filters must be matched to the phosphors used in the backlighting of AMLCDs. Present backlighting of full-color VGA panels requires so much power that portable personal computer (PC) batteries only last about an hour. The color filters and the phosphors for backlighting must be treated as a system. This currently is not the practice of the flat-panel display industry. Color filters contain either dyes or pigments. Dyes have problems associated with fading over time due to temperature cycling. Pigments have challenges of controlling variations in size, maintaining their stability, and scattering issues. Blue filters generally have high absorption that leads to more power consumption. In order to improve contrast ratios, a black surround is placed around each color pixel. If any holes occur in either the surround or the filter itself, annoying bright spots will appear in the completed display.

People assumed incorrectly that today's color filters were acceptable. The low yield of color filters is an issue. Very few companies produce dyes for LCDs and only one company produces pigmented filters. Apparently, these companies have not invested adequately to meet the yield requirements of LCDs and they charge excessively (according to display makers). Most of the investments are devoted to producing the thin-film transistors and LCD assemblies.

Phosphors

Like the glass substrates mentioned above, phosphors occur in most display technologies. They may be excited by such means as electrons or ultraviolet light from gas discharges. The parameters for which better and faster measurements would be helpful are efficiency of the phosphor for producing the correct color, chromaticity, and brightness. In addition, there are ample opportunities for bandgap engineering of phosphor materials.

Driver Chips and Integrated Circuits

It is interesting to note that potentially dirty processes such as plasma-enhanced chemical vapor deposition (PECVD) are limited to the back end of most semiconductor (mostly crystalline silicon) processing lines whereas such problematic processes as PECVD are used in the critical front end of making flat-panel displays. The drivers for displays typically operate at around 15 V instead of the 5 V for semiconductor circuits. Functionality and performance improve with increasing crystallinity, that is, as one goes from using amorphous silicon (a-Si), through multi-crystalline silicon and polycrystalline silicon (poly-Si), to single crystal silicon, the performance increases. But, in general, so do the processing temperatures. One goal for flat-panel displays is to develop as low a processing temperature as possible for placing transistors on glass substrates. The goal would be single-crystal silicon transistors processed on glass at temperatures below 300°C.

Typical thin-film transistors for displays have design rules of about 2 μm for panels now as large as 30 cm. The number of suppliers of large masks to accomplish this is very small.

Higher yields for making the thin-film transistors will probably be achieved in part by real-time, in-line process monitoring, process simulation, and process control.

Enhancements for both amorphous and polycrystalline silicon would be very timely. Amorphous-silicon transistors can be improved through computer simulations that lead to better designs. A considerable knowledge base exists for silicon-hydrogen chemistry that could result in lower processing temperatures, but benefits from this knowledge have not been transferred to tools for making displays. Amorphous-silicon transistors have poor mobilities but are adequate for keeping leakage currents to a minimum. On the other hand, polycrystalline silicon transistors have higher mobilities but tend to have problems with leakage currents.

Contact and Proximity Exposure Tools

Many of the contact and proximity exposure tools used in making displays are traceable to those used in making silicon circuits. Much higher throughputs for such tools are needed. Makers of displays probably should not continue to scale semiconductor equipment but should consider more innovative approaches.

Plasma Etching

Dip etching and spray etching are too crude and are based on old designs and old-fashioned chemistry. New chemical processes are needed to increase throughput, reduce waste of expensive materials, and make safe, environmentally correct disposal of any waste practical. Dry etching is now preferred for better control and produces far fewer wastes from the process. But, the present etching methods, adapted from semiconductor processing and based on the chemistry of carbon tetrafluoride and oxygen, may not be optimum for flat-panel displays.

High Resolution Packaging

High resolution panels contain about 3 million color pixels and require approximately 3000 connections for the columns and 1000 connections for the lines in the display. This means that reliable and cheap connecting schemes with pitches down to 15 μm will be needed for small panels used in projection systems. Large, direct-view panels will not require such small pitches.

The flat-panel display industry needs agreed-upon ways to test completed panels for such quantities as brightness, gray scale, color purity, and pixel speed. The many contributors to making displays must collectively decide on what is required and, if possible, develop a consensus for acceptable measurements, tests, and evaluation methods for completed or nearly completed displays.

New Materials for LCDs

New ways for making encapsulated liquid crystals are needed so that the display functions with perhaps only one polarizer and requires only ambient, reflected light (such as the images printed on paper). This would greatly reduce power consumption. Another area of need is to make liquid crystals that respond linearly to the applied voltage for increased display performance and control of its pixels. A third area is developing liquid crystals that are suitable for addressing the pixel with other than active transistors.

Psychovisual and Psychophysical Modeling

In the final analysis, the human eye determines the merits of a given display technology. Greater understanding of this human interface with the display is needed. Much of today's understanding is based on previous simulations and modeling of cathode-ray tubes for which the application to the display technologies mentioned above may not be appropriate or may even be misleading.

TABLE 2
Measurements and Materials Technical Challenges for the Manufacturing of Active Matrix Liquid Crystal Displays (AMLCD)

Issues	Impact	
	Cost/Yield	Performance
Highest Priority:		
Substrate particle inspection for uncoated, coated, and patterned layers	x	(x)
Less expensive color filters	x	(x)
Process materials development for active matrices	(x)	x
New liquid crystals for reflective mode operation (this is a long-term and high risk challenge)		
Medium Priority:		x
Substrate cleaning	x	
Resist and polyamide coatings	x	
Alignment layer	x	(x)
Packaging	(x)	x
Lower Priority:		
Flatness measurements	x	(x)
Properties of films measurements	x	
Modeling for less time-to-market		x
Drivers and IC circuits	(x)	x

The remaining technical challenges presented in the text and that apply to AMLCDs are considered important but not as important as those listed in this table.

TABLE 3
Measurements and Materials Technical Challenges for Manufacturing of Plasma Displays

Issues	Impact	
	Cost/Yield	Performance
Highest Priority:		
Substrate inspection and patterned layers	x	(x)
Phosphors		x
Packaging	x	(x)
Medium Priority:		
Inspection of coatings	x	
Driver chips and IC circuits		x
Resist and polyamide coatings	x	
Contact exposure tools	x	

The remaining technical challenges presented in the text and that apply to plasma displays are considered important but not as important as those listed in this table.

TABLE 4
Measurements and Materials Technical Challenges for the Manufacturing of Electroluminescent Displays

Issues	Impact	
	Cost/Yield	Performance
Highest Priority:		
Inspection of incoming materials	x	
Blue phosphors	(x)	x
Drivers and IC circuits		x
Medium Priority:		
Packaging and chip-on-glass	x	(x)
Coating		x
Contact proximity exposure tools		x

The remaining technical challenges presented in the text and that apply to electroluminescent displays are considered important but not as important as those listed in this table.

TABLE 5
Measurements and Technical Challenges for the Manufacturing of Active Matrix Liquid Crystal Displays (AMLCD)

Issues	Mat	Man	Mea
Highest Priority:			
Substrate particle inspection for uncoated, coated, and patterned layers		C	S
Less expensive color filters	N,I	C	O
Materials development for active matrices	N	P	
New liquid crystals for reflective mode operation	N	P	O
Medium Priority:			
Substrate cleaning		C	S
Resist and polyamide coatings		C	
Alignment layer	N,T	C	M
Packaging	N,I	P	L

The remaining technical challenges presented in the text and that apply to AMLCDs are considered important but not as important as those listed in this table.

Mat = Materials
  N = new
  I = improved (such as better carrier mobility, lower absorption, more efficient, lower temperature processing, etc.)
  T = research for new techniques that are inherently clean

Man = Manufacturing
  C = cost/yield
  P = performance

Mea = Measurement
  S = chemical identity and quantity
  O = optical properties
  M = microstructure features
  L = lifetime and reliability

TABLE 6
Measurements and Technical Challenges for
the Manufacturing of Plasma Displays

Issues	Mat	Man	Mea
Highest Priority:			
Substrate inspection and patterned layers		C	S
Phosphors	N,I	P	W,L
Packaging	N,I	P	L
Medium Priority:			
Inspection of coating		C	U
Driver chips and IC circuits	I	P	
Resist and polyamide coatings		C	
Contact exposure tools		C	A

The remaining technical challenges presented in the text and that apply to plasma displays are considered important but not as important as those listed in this table.

Mat = Materials
  N = new
  I = improved (such as better carrier mobility, lower absorption, more efficient, lower temperature processing, etc.)

Man = Manufacturing
  C = cost/yield
  P = performance

Mea = Measurement
  S = chemical identity and quantity
  W = lumens per Watt
  L = lifetime and reliability
  U = uniformity in thickness and correct patterns and lithography
  A = large area lithography and uniform illumination

TABLE 7
Measurements and Technical Challenges for
the Manufacturing of Electoluminescent Displays

Issues	Mat	Man	Mea
Highest Priority:			
Inspection of incoming materials		C	O,E
Blue phosphors	N,I	P	W,L
Drivers and IC circuits	I	P	
Medium Priority:			
Packaging and chip-on-glass	N,I	C,P	L
Coating	N	C	U
Contact proximity exposure tools		C	A

The remaining technical challenges presented in the text and that apply to electroluminescent displays are considered important but not as important as those listed in this table.

Mat = Materials
  N = new
  I = improved (such as better carrier mobility, lower absorption, more efficient, lower temperature processing, etc.)

Man = Manufacturing
  C = cost/yield
  P = performance

Mea = Measurement
  O = optical properties
  E = electrical and electronic properties
  W = lumens per Watt
  L = lifetime and reliability
  A = large area lithography and uniform illumination

STORAGE

Jonathan Hardis, NIST
Gary Bjorklund, IBM

Participants

The core of the working group consisted of

Gary Bjorklund, Chairman	IBM
Jonathan Hardis, Reporter	NIST
Randall Babbitt	Boeing
Wilfred Lenth	IBM Almaden Research
Masud Mansuripur	Univ. of Arizona
William R. Ott	NIST
Yuan-sheng Tyan	Eastman Kodak Co.
Francis W. Wang	NIST

Other participants included

John Batey	IBM
Joe Carpenter	NIST
Tom Davis	NIST
Alastair Glass	AT&T Bell Labs
Freddy Khoury	NIST
Raj Rajasekharan	DEC/Cornell
Jerry Willenbring	Tamarack Storage Devices
Joe Williams	IBM
Lambertus Hesselink	Stanford, was unable to attend and participated via videotape.

Scope

The working group discussed three topics: laser discs, holographic memory, and persistent spectral holeburning (PSHB). The first enjoys wide commercial success, in such forms as compact discs (CDs) for audio and computer data, larger format discs for video, magneto-optical read/write computer drives, and high capacity WORM (write once, read many) computer drives. The working group discussed additional aspects of laser discs, such as alternate technologies that are not widely commercialized and have prospects for improving current products. Holographic memory is an experimental storage mechanism that records throughout the volume of a material, rather than just at its surface. The promise of this technique is greater storage density and faster data transfer rates. PSHB is another experimental process that promises extremely fast data transfer rates and a natural application to mathematical problems involving convolutions and correlations (such as pattern recognition).

Laser Discs

Laser disc sales today are ~$6 billion, mostly in the form of audio CDs, with a growth projected to ~$25 billion by 2000. Fueling this growth will be data-intensive computer applications, such as document imaging, image processing, and multi-media (i.e., video) source material. Most of the discussion centered on technology and methods for improving current read/write technology, with the key parameters being storage capacity, data rate, and manufacturing cost. (Access time was not considered an optical issue.) The capacity of the disc is determined by its size and the wavelength, λ, of the laser. The size of the diffraction-limited spot is proportional to λ^2 and the capacity is proportional to λ^{-2}; thus, if the wavelength is halved, the capacity of a disc is quadrupled. Thus, research interests lean toward developing blue or ultraviolet diode lasers (for their shorter wavelengths) and disc materials that would be compatible with this advance.

The working group discussed aspects of the disc that need further research and development. For example, the aspects included the recording mechanism (magneto-optical or phase change) and the active material to implement it; the substrate (what encapsulates the disc); and additional layers required in the disk (such as dielectrics) that provide optical index matching, passivation, and necessary thermal behavior. While the CD format for consumer use is likely to be stable for some time given the installed base of products in the field, the short product cycles in the computer industry can allow a major advance in performance or cost to reach market quickly, even if the underlying technical approaches differ radically from current products.

Table 8 outlines in more detail the recommended research areas, primarily materials-related ones. The key area here is the active recording material, magneto-optical (MO) or phase-change, and the research and coordination required to advance the current art. The working group felt that industry is already pursuing the most commercially promising, proprietary materials and processes, but many others are neglected due to budget and time constraints. There is also the need for "big picture" support, such as systematically studying basic materials properties (such as magnetic and thermal ones) and synthesizing existing, scattered data on material families. This fundamental and exploratory research would complement similar work already being done in industrial labs, which would then extend it into product development.

Substrate and dielectric issues are similarly detailed in Table 8. All of these elements of a laser disc need to be improved in tandem in order to advance the state-of-the-art, providing many opportunities for participation by researchers in different fields.

Holographic Storage

While the techniques for implementing this recording method are being explored in the laboratory, no material currently exists that has the required properties for commercial acceptance. These properties include a large diffraction efficiency, a lack of impurities which cause noise (errors), and an ability to easily record while resisting unwanted erasure and degradation. Continued fundamental and exploratory research is required on classes of photorefractive materials that could be applied to this technique, on fabrication methods to produce such materials with good optical quality, and on methods of using those materials in holographic recording systems. Recommended research areas are outlined in Table 9.

Persistent Spectral Holeburning

PSHB is a laboratory technique which today requires cryogenic temperatures (4.5 K, liquid helium) to operate. This complexity precludes PSHB for consideration in most applications. However, the process is naturally suited for applications requiring continuous, high-speed correlations, such as pattern recognition. That suitability and a basic scientific interest in the materials that enable this technique, fuel continued laboratory investigations. Recommended areas of research are given in Table 10.

TABLE 8

Summary of Priority Issues Identified

OPTICAL STORAGE / LASER DISCS

Issues in approximate order of priority	Mat	Man	Mea
Highest Priority:			
Research directed toward developing blue or ultraviolet solid state (diode) laser	x		
Magneto-optical (MO) recording:			
Compile existing but widely scattered data on the wide variety of thin-film material systems which have been investigated by industry as recording media.	x		
Develop techniques for measuring the magnetic properties, such as flux pinning and coercivity, of optically active thin-film materials.			x
Investigate recording material systems that industry judges to be too speculative for their commercial research programs, such as rare-earth/transition-metal alloys and Co:Pt superlattices.	x		x
Phase-change recording:			
Compile existing but widely scattered data on the wide variety of alloys which have been investigated by industry as recording media.	x		
Produce phase diagrams for candidate alloy systems, such as Sb:InSn and TeSbGe	x		x
Measure thermodynamic properties of alloy systems, such as thermal conductivities, specific heats, and heats of melting; develop techniques for making these measurements efficiently.	x		x
Investigate recording material systems that industry judges to be too speculative for their commercial research programs	x		x

TABLE 8, Continued
Summary of Priority Issues Identified
OPTICAL STORAGE / LASER DISCS

Issues in approximate order of priority	Mat	Man	Mea
Substrates:			
Improve manufacturing (stamping and injection molding) techniques to reduce stress-induced birefringence and self-orientation, improve the surface finish, and increase the flatness of the disc.		x	
Investigate new polymer blends that would allow for thinner discs, with better optical properties, less adsorption of water and oxygen (which give optical discs limited life), less wear in normal handling, less photochemical degradation, and tolerance to the higher temperatures required for MO sputtering.	x		
Dielectrics:			
Improve manufacturing techniques for depositing thin layers, improving adhesion and reducing thermal mismatches, at reduced cost.		x	
Investigate new materials for use at shorter wavelengths.	x		
Other Priorities:			
Develop organic dyes for write-once discs.	x		
Develop recording techniques using mark-length modulation.		x	

TABLE 9
Summary of Priority Issues Identified
OPTICAL STORAGE/HOLOGRAPHIC STORAGE

Issues in approximate order of priority	Mat	Man	Mea
Highest Priority:			
Develop crystal growth techniques to reduce striations and other defects.	x		
Develop photorefractive polymers with appropriate mix of optical properties.	x		

TABLE 10
Summary of Priority Issues Identified
OPTICAL STORAGE/PERSISTENT SPECTRAL HOLEBURNING

Issues in approximate order of priority	Mat	Man	Mea
Highest Priority:			
Develop crystal growth techniques for candidate materials.	x		
Develop photon-gated materials with favorable energy-level scheme.	x		
Other Priorities:			
Theoretical studies of the energy levels and lifetimes of dopants in crystal hosts.	x		
Theoretical studies of the energy levels (and their lifetimes) of isolated organic molecules embedded in glassy or polymer binders.	x		x

ACTIVE DEVICES

Michael A. Schen, NIST

Participants

The comments and recommendations presented within this section represent a consensus of opinion achieved by the following persons who contributed substantially to the discussion.

Huan-Wun Yen, Chairman	Hughes Research Laboratories
Michael Schen, Reporter	NIST
Gary Boyd	3M Company
Lap-Tak Cheng	DuPont
Charles Cox	MIT Lincoln Laboratories
Stephen Freiman	NIST
Anthony Garito	University of Pennsylvania
Joseph Pellegrino	NIST
Alan Pine	NIST
Paras Prasad	State University of New York at Buffalo
Hyun-Nam Yoon	Hoechst Celanese Co.
Adrian Popa	Hughes Research Laboratories (original organizer of the working group, unable to attend the workshop)

Three opening presentations were made to the working group by Charles Cox (Inorganic Crystals), Huan-Wun Yen (III-V Semiconductors), and Hyun-Nam Yoon (Organic Polymers).

Active Optical Materials

For the purpose of this workshop and report, an active optical device was defined as...

> ... *a component, other than a laser or detector, which provides optical control via an external electrical, acoustic, or optical signal.*

Within the context of this definition, three materials classes were considered by the working group. Table 11 lists these classes and identifies the more important materials that were discussed.

TABLE 11
Classification of Active Materials

Inorganic Crystals
• Lithium Niobate ($LiNbO_3$)
• Alternate Inorganic Crystals
- Potassium Niobate ($KNbO_3$)
- Potassium Titanyl Phosphate ($KTiOPO_4$)
- Lithium Tantalate ($LiTaO_3$)
- Strontium Barium Niobate ($Sr_{5-x}Ba_xNb_{10}O_{30}$)
- Beta-Barium Borate (β-BaB_2O_4)
- Lithium Triborate (LiB_3O_5)
III-V Semiconductors
• Gallium Arsenide (GaAs)
• Aluminum Gallium Arsenide (AlGaAs)
• Aluminum Gallium Indium Phosphide (AlGaInP)
Organic Polymers
• Electro-Optic Polymers
- Guest/Host Materials
- Nonlinear Optical (NLO)-Dye Functionalized Thermoplastics and Thermosets
• Photorefractive Polymers[1]
• Third Order NLO Polymers[1]

[1] These materials were not discussed by the working group due to a lack of time but were recognized as important future materials that should be treated in future forums.

Commercial Applications of Active Optical Devices

A limited variety of active optical devices are commercially available today and are essentially based on a few inorganic single-crystal materials. This includes lithium niobate ($LiNbO_3$), beta-barium borate (β-BaB_2O_4), and lithium triborate (LiB_3O_5). Applications include $LiNbO_3$ for externally controlled electro-optic (EO) modulators, and β-BaB_2O_4 and LiB_3O_5 crystals as higher order harmonic generators for Nd:YAG lasers. They are also used in optical parametric generators as tunable light sources because of their high optical damage threshold. Present day active devices exist as discrete, stand-alone modules and are characteristically expensive. For example, a fiber-attached, lithium niobate electro-optic modulator costs approximately $5000. No devices based on III-V semiconductors are sold in abundance due to the impracticality of this technology for creating discrete devices and the many technical problems that remain before integrated devices can be realized. No commercial devices derived from nonlinear optical (NLO) organic polymers exist after a decade of research, though this technology shows promise for obtaining cost- and performance-effective devices.

Harmonic generators for laser frequency conversion along with electro-optic modulators for optical communications presently have significant commercial use. Devices are fabricated and utilized as stand-alone, discrete devices and are coupled to the optical beam either by direct-launch or through fiber attachment ("pigtailing"). Advancements in material, design, manufacturing, and system requirements are propelling device technology towards monolithic structures. This evolutionary trend builds upon the micrometer-scale, multi-functional characteristics of present day, silicon-based integrated circuit (IC) technology. Consequently, micrometer-scale processing of all three material classes for creating integrated structures is growing in importance. Process modeling, sensing, and control will also grow in importance as material scientists are required to meet the needs of integrated device engineers.

Over the next ten years, an array of active devices are envisioned to become important to U.S. civilian markets. If consideration is limited to applications likely to reach the marketplace in the 1990s, two principal arenas for optical systems incorporating active devices are envisioned -- **digital communications** and **analog information processing**. Table 12 lists some of the commercial applications believed possible for each of these two arenas.

Table 13 lists the various devices from the three separate material classes that will support the above applications. Because performance requirements vary with device application, devices incorporating materials from all three material classes will likely be developed according to the specific attributes of the individual material. For both inorganic single crystals and organic polymers, the devices listed may be in the form of discrete, stand-alone modules or as integrated devices. Attributes of III-V semiconductors, on the other hand, lend themselves to use within fully integrated designs, and few, if any, discrete devices are expected.

TABLE 12
Commercial Applications for Active Devices

Communications (mainly digital)
• Telecommunications - switchable optical networks
• Data communications - reconfigurable links, interconnects
• Cable Access Television (CATV) - broadcast networks and switching
Information Processing (mainly analog)
• Microwave links - antenna remoting
• Sensors - fiber optic gyro, radar
• Image and Signal Processing - spatial light modulator
• Data Storage - second harmonic generation, volume holography
• Tunable Sources - frequency conversion

TABLE 13
Anticipated Commercial Devices

Inorganic Single Crystals
• Lithium Niobate, KTiOPO$_4$: splitters, switches, phase shifters, electro-optic and acousto-optic modulators mini blue-green lasers
• Alternate Inorganic Crystals (β-BaB$_2$O$_4$, LiB$_3$O$_5$, KNbO$_3$): harmonic generators, mini blue-green lasers
III-V Semiconductors
• polarization convertors, amplifiers, switches, modulators, sensors
Organic Polymers
• Electro-Optic Polymers: modulators, switches, reconfigurable optical interconnects
• Photorefractive Polymers: (not discussed)
• Third Order NLO Polymers: (not discussed)

Materials Issues

In order to capture future markets, active devices will have to exhibit high performance at low costs. Both cost and performance are of primary concerns for inorganic crystals, III-V semiconductors, and organic polymers.

The working group believes that an essential component of any coordinated active materials R&D investment strategy should be the development of advanced materials in which the material's figure-of-merit (FOM) is evaluated. A material's FOM is the combination of primary linear and nonlinear optical properties -- such as refractive index, linear absorption coefficient, and electro-optic coefficient -- and secondary properties -- such as processability, oxidative and thermal stability, etc. The importance of time-to-market in light of global competition dictates generic, precompetitive technology "know-how" be directed into an information pool and broadly distributed to U.S. industry. An R&D strategy based on the old paradigm of intense industrial competition throughout all phases of the generic research and sequential product development cycle, is seen as inappropriate by members of the working group.

The working group believes that present market demands are too small to support a wide array of materials development for active devices. Rapid expansion in market potential would occur if the cost of developing and manufacturing devices can be reduced and technical data -- such as figures-of-merit, standard reference data (SRD), etc. -- can be compiled and broadly disseminated. The working group believes that R&D investment should be focused on developing needed micro-fabrication "know-how" and assessing figures-of-merit of materials which appear promising for meeting performance needs of high industrial priority technical applications.

A number of desirable material characteristics are needed of second-order NLO materials to enable development of active devices. Materials should exhibit:

- large second-order nonlinear optical susceptibility (χ^2),
- low optical and dielectric losses,
- impedance matching to electronic interfaces,
- optically smooth cuts or patterns for device fabrication, and
- micrometer-scale processability for forming waveguiding domains.

From the working group discussions, certain cross-cutting issues emerged pertaining to materials in all three material classes. Table 14 lists these universal issues and lists materials-, manufacturing-, and measurement-related research that would help surmount the individual issues.

TABLE 14
Cross-Cutting Needs
ACTIVE DEVICES

UNIVERSAL ISSUE	RESEARCH AGENDA		
Highest Priority	Mat	Man	Mea
Lower Manufacturing Costs	P, S, SRM	D, F, G, P, T, W, Y	B, D, F, I, SRD, T
Improve Information Dissemination Across Disciplines	SRM	D, E, G	B, D, SRD,T
Broaden Acceptance of the Technology	SRM	D, E, T	F, D, MS, SRD

Materials (Mat):
- I = improved performance of existing materials
- N = new materials design, synthesis, and/or processing
- P = purity and control of contaminants
- R = structure / property relationship
- S = improved synthesis and/or processing of existing materials
- SRM = standard reference material

Manufacturing (Man):
- D = device prototype development
- E = concurrent engineering methodologies
- F = fiber attachment technologies
- G = shared, generic, precompetitive technology
- I = intelligent design based on materials data
- M = manufacturing improvements by material suppliers
- P = process measurement, control and/or testing for improved quality
- S = scale-up of material and/or technology from laboratory curiosity
- T = manufacturing tolerances
- W = waveguide and thin-film manufacturing technology
- Y = improve yield

Measurements (Mea):
- B = benchmarking to defacto industry standards such as lithium niobate
- C = chemical and/or environmental stability
- D = material property data and/or databases
- DF = characterization of defect structures
- E = electrical properties such as conductivity, permittivity, etc.
- F = performance-based figure-of-merit evaluation
- I = information and data exchange
- MM = morphology, microstructure, and/or orientation
- MS = modeling and simulation
- OL = linear optical performance, stability, or damage
- ON = nonlinear optical performance, stability, or damage
- P = predictive, long-term reliability
- SRD = standard reference data
- T = performance tolerances
- W = waveguide performance / attenuation

Inorganic Crystals

The development of a counterpart to silicon for photonics is needed to usher in widespread use of active device materials. The working group believes that a near-term goal should be to target R&D investments that will build technical confidence in a material -- such as lithium niobate -- that will facilitate adoption across an array of applications.

Lithium niobate:

After two decades of work, lithium niobate ($LiNbO_3$) continues to dominate laboratory-based photonic materials R&D, device development, fabrication, and production. It is the only material to be used broadly within the commercial marketplace, finding greatest application as the active element within discrete electro-optic modulators. Lithium niobate devices are finding application as fiber-optic gyros for the control of spatial orientation of mobile platforms such as aircraft and measuring machines, and modulators for emerging information technology markets such as cable access television (CATV). In the short term (3 years or less), inorganic single crystal devices will primarily be used for frequency conversion and electro-optic modulation.

Optical quality lithium niobate single crystals have been commercially available for many years. Given this, a big question is why lithium niobate active devices are only used on a limited scale. A packaged, fiber-coupled lithium niobate EO modulator costs in the range of $5000 -- a price much too unrealistic for widespread CATV application, for example. Of this, packaging (including fiber attachment) is the major cost component, representing nearly 60% of the total price of the device. Cost, performance, demand, technical impediments, and other factors are preventing market penetration and large scale utilization of active devices. It was the unified opinion of the working group that reasons for limited utilization of active devices are numerous and complex and that further consideration is needed by a fully represented industry team.

Much of the science and technology investment in lithium niobate stems from the characteristic ease with which single crystals may be cut and fabricated into discrete devices. The technical advantages which have emerged from this investment include:

- high electro-optic coefficient,
- ability to fabricate low-loss waveguides, and
- amenable to discrete device fabrication.

All of this has led to large knowledge and experience bases for lithium niobate. Consequently, lithium niobate is viewed as a "meter-stick" against which characteristics of all other active materials are measured.

On the other hand, lithium niobate exhibits numerous technical disadvantages which, if left unsolved, will limit use of this material in other applications. For example:

- Intrinsic Material Characteristics

  Lithium niobate performance characteristics will likely prevent it from becoming the "silicon" of the photonics industry due to dc-drift, significant pyroelectric and piezoelectric character, and optical damage at high laser powers.

- Polarization Sensitive Coefficient

  The EO coefficient of lithium niobate is polarization dependent. Beam polarization must be preserved in the attached fiber and device, thereby escalating cost.

- Frequency Dependent Performance

  The electro-optic sensitivity of lithium niobate falls off at long wavelengths narrowing the performance window of devices for information processing.

- Anisotropic Thermal Expansion

  The thermal expansion coefficient of lithium niobate highly anisotropic (ca. 7). This makes it difficult to thermally match to other materials, thereby affecting device manufacturability, reliability, and operating temperatures.

- Performance Characteristics Vary Among Producers

  Lithium niobate performance tolerance and standard reference data, and standard reference materials do not exist leading to widely varying performance specifications among producers.

- Processing Dependent Device Performance

  Defect structures and material properties are intimately linked to processing methods used in fabricating single crystal slabs and waveguide structures, giving rise to artifacts and device performance limitations.

- Difficult to Fabricate Integrated Devices

  Lithium niobate is nearly inert, with no means of conducting isotropic or anisotropic chemical etching. Consequently, monolithic, microelectro-optic devices may be nearly impossible to manufacture using this material.

- Devices Too Costly

Stand-alone devices are expensive, costing approximately $5000 for a fiber-attached electro-optic modulator. Expensive crystal growth techniques, poor processing control, unrefined fiber attachment methods, and unresolved packaging problems all lead to low manufacturing yields and high costs.

Alternate inorganic crystals:

A number of inorganic crystals exhibit properties that make them attractive alternatives to lithium niobate for specific applications. Table 15 lists the more important "next generation" inorganic single crystals along with their performance attributes relative to lithium niobate, and possible future devices. Many of the materials listed in Table 15, excluding $KTiOPO_4$ and $LiTaO_3$, exhibit poor long-term and temperature stability of the electro-optic coefficient - a characteristic believed linked to their intrinsically large EO coefficient. $KNbO_3$ also has a tendency to depole when exposed to thermal or mechanical shock due to a facile crystal-crystal phase transition.

At present, these materials are being investigated in the form of bulk single crystals -- similar to lithium niobate itself. Given, however, pressures to use these materials within integrated optic (IO) structures, a central research goal is the development of the necessary science and technology base to enable thin-film fabrication and processing for generating three-dimensional channel waveguides suitable for IO applications.

Table 16 summarizes the most salient technical issues confronting R&D for inorganic crystals.

III-V Semiconductors

Less time was devoted to III-V semiconductors because of a limited attendance of III-V experts in the working group and because it was believed that issues for these materials would be discussed by the "Sources and Detectors" working group.

Research on III-V semiconductors (III-Vs) is directed to the development of integrated, even stackable, optical devices. Because of the vast knowledge base that has accrued in the design and processing of inorganic semiconductors and the wide range of nonlinear effects exhibited by III-Vs, the largest impact of these materials is believed to be in optoelectronic integrated circuits (OEIC). Cost and complex fabrication processes generally make these materials ill-suited for discrete photonic devices - unlike the inorganic crystals and organic polymers.

A major problem confronting the synthesis and fabrication of all III-V compounds is the high cost of processing equipment. The initial cost of a reactor/process chamber is nearly $0.5 million and operating costs are extremely high. A related issue is the likelihood of reactor contamination when different source materials are used. Consequently, reactors/processors tend to be dedicated to a single material preparation thereby escalating costs.

TABLE 15
Attributes and Applications of Alternate Inorganic Crystals

Material	Attribute	Applications
Potassium Niobate ($KNbO_3$)	large electro-optic coefficient	modulators
Potassium Titanyl Phosphate ($KTiOPO_4$)	large electro-optic coefficient, amenable to waveguide fabrication using 1-D ion implantation	integrated optical waveguides, modulators, frequency conversion, parametric oscillator
Lithium Tantalate ($LiTaO_3$)	high optical damage resistance at short wavelengths	diode laser frequency conversion
Strontium Barium Niobate ($Sr_{5-x}Ba_xNb_{10}O_{30}$)	large electro-optic coefficient	
Beta-Barium Borate (β-BaB_2O_4)	modest electro-optic coefficient, superior high-energy optical damage resistance	diode laser frequency conversion
Lithium Triborate (LiB_3O_5)	modest electro-optic coefficient, superior high-energy optical damage resistance	diode laser frequency conversion

TABLE 16
Issues for Inorganic Crystals
ACTIVE DEVICES

Issues	Mat	Man	Mea
Highest Priority			
Interrelationship between process and properties ($LiNbO_3$, $LiTaO_3$, β-BaB_2O_4, LiB_3O_5, etc.)	N, R, S	M, P, S,	DF, MM, OL, ON, SRD, T
$LiNbO_3$ - Variable intrinsic material properties	P, SRM	M, P	SRD
Alternate single crystals - incomplete mapping of material properties	P, R, S	S, W	C, D, DF, E, F, MM, MS, OL, ON, P, W
Alternate single crystals - translation to thin-film structures	R, S	M, S, W	D, MM, W
Lower Priority			
$LiNbO_3$ - Difficult to fashion waveguides	S	M, W, I	
$LiNbO_3$ - Undesirable thermal, frequency, and polarization-dependent performance	N, R	I, M	SRD, D
$LiNbO_3$ - Devices too large	I	Y	W
Alternate single crystals - poor long-term and temperature stability	R, S	M	B, C, D, DF, P, SRD, T

See Legend at bottom of Table 14 for explanations of abbreviations

Beyond equipment considerations, a major issue confronting development of cost-effective III-V semiconductor optical devices is quality of materials and repeatability of process along the entire development cycle. Substrate and source materials vary from batch to batch. Substrates are easily contaminated thereby exhibiting unexpected properties. Semiconductor synthesis and growth is not well controlled giving rise to structure variations with each preparation. These and other issues highlight the need for the following advancements:

- improved NLO performance,
- improved purity and consistency of substrate and source materials,
- non-toxic dopants to replace presently used toxic compounds,
- improvements in uniformity and repeatability of crystal growth process,
- establishment of material properties tolerance data for promising materials,
- development of in-situ measurement and sensing of MBE/MOCVD growth process, and
- investigations of alternate growth techniques to overcome high initial and operating cost of MBE or MOCVD growth apparatus.

In general, processing advancements are needed to push this technology into the realm of being able to repeatably produce a large number of waveguide structures at a reasonable price. The high overall toxicity of many of the III-V starting materials also deters widespread adoption of this technology and requires handling safeguards which escalate complexity and cost. Table 17 lists the most salient technology issues and research items confronting III-V semiconductors assembled by the working group.

Organic Polymers

Experiments studying the physics of organic nonlinear optics, the synthesis of new materials, and the characterization of "primary" optical properties has dominated research activities on organic polymers to date. The most promising initial application of polymers as an active device element will be for electro-optic modulators. Technical advancements in second order NLO polymer technology for electro-optic applications has outpaced advancements in other materials such as third-order NLO polymers and photorefractive polymers. However, rapid advancements in photorefractive polymers for data storage, signals that these materials may become important in the future. Though photorefractive and third-order NLO polymers show promise for commercial application, the working group believed that they will require much greater laboratory research before products could be realized. Future workshops will need to examine the issues impeding insertion of these materials into optical devices should

TABLE 17
Issues for III-V Semiconductors
ACTIVE DEVICES

Issues	Mat	Man	Mea
Highest Priority			
Poor quality and consistency of substrate and source materials	P, S	G, M, P, T	D
Variability during processing	P, R, S	P, S, T, Y	
Lower Priority			
Highly toxic dopant materials	N, P		
Highly sophisticated and costly manufacturing	N, S, SRM	G, I	I, MS

See Legend at bottom of Table 14 for explanation of abbreviations

technological improvements continue. Consequently, the present discussions are restricted to second-order NLO polymers only.

Polymers with electro-optic coefficients near 50-70 pm/V are available. In general, the research emphasis for second-order NLO polymers is increasingly being directed towards developing "overall" performance and reliability data, process "know-how," and fabrication methodologies for creating active devices. Issues like long-term performance, optical and thermal stability, waveguide fabrication, and fiber "pig-tailing" are receiving greater attention. The development of an electro-optic polymer with an electro-optic coefficient in the area of 100 pm/V with good "secondary" properties will create great excitement in the photonics community.

There are four fundamental issues confronting researchers in this area: stability, property mapping, optical loss, and waveguide fabrication. Major stability issues include thermal, orientational, photochemical, and oxidative durability of both the NLO dye and the polymer. These are areas where better materials, measurement methods, and data are needed. Specifically, better data on long-term stability of dyes in the visible and near-ultraviolet spectra are needed. It is believed that a juncture is being approached between high optical performance and deterioration of secondary properties such as chemical, photochemical, and oxidative stabilities for present day organic NLO dye/polymer combinations. Consequently, design and synthesis of new chromophores with very different structures is needed.

A materials success will depend on data becoming available that represents the entire spectrum of properties needed for insertion of the material into a device. There is a strong need for generating "primary" and "secondary" performance data on most promising polymer materials. Related to this is the recognized need for establishing performance standards or specifications for these materials. Table 18 illustrates this concept by representing the material requirements that were developed for building an integrated optical polymer device. Establishment of "global" performance standards for materials will improve quality, reliability, and testing of both materials and devices as each become commercially significant. It will also assist the evaluation of a new material's "figure-of-merit" so as to provide researchers and systems designers a basis for evaluating the relative merits of materials.

Reductions in optical losses require development of optically clean materials and improved fabrication processes. Intrinsic losses as well as parasitic losses are important problems for today's polymer waveguiding structures. Intrinsic losses are characteristic of the material whereas parasitic losses are introduced through material manipulation, processing, or device fabrication. Transparency in the near-infrared, specifically, at 1.3 and 1.55 μm, needs to be improved. Reducing intrinsic losses will require design of alternate polymer structures. Presently, intrinsic absorptive losses are nearly 1 dB/cm at 1.55 μm and are too large for most applications. At 1.3 μm intrinsic losses are about 0.3 dB/cm and are at the higher limit for building devices. Subsequent processing into waveguides generally increases these losses even further. Reducing losses below present levels through improved processing of existing materials is needed. There has been and continues to be great efforts directed towards reducing the intrinsic losses, but little concerted effort has been directed towards reducing parasitic losses. Procedures, measurement methods, and translation of laboratory-based fabrication methods have never been adequately addressed and are major obstacles to large-scale future usage of polymers. This is an enabling technology critical to all organic polymer-based photonic devices.

It was agreed that increased emphasis on waveguide processing is critical for developing cost-effective fabrication technologies. Presently, process development experiments are often sloppily done, and there is little coordination among research centers or between the research and manufacturing laboratories. Waveguide processing has implications both on cost - through their manufacture -- but also on performance, especially in the form of optical loss. For example, the best overall losses to date with a polymer is 1 dB/cm at 1.3 μm from Hoechst Celanese for single-mode waveguide. Of this, 0.7 dB/cm is due to insertion losses. It was the belief of the group that overall losses -- due substantially to waveguide fabrication methods -- have to come down to 0.5 dB/cm to be practical for monolithic devices. Waveguide processing of organic polymers giving low-loss structures is an enabling technology that will allow many promising organic polymers to be broadly evaluated as electro-optic or photorefractive media.

A specific proposal strongly endorsed by the entire group was to benchmark a test polymer electro-optic modulator to a similar lithium niobate device. This was viewed especially

TABLE 18
Materials Requirements for Integrated Optical Polymer Devices[1]
ACTIVE DEVICES

NLO MOLECULAR GUEST		
Optical Properties	**Acceptable**	**Preferred**
Electro-optic coefficient (pm/V)	30	100
Absorption loss (dB/cm)	<1.0	<0.1
Scattering loss (dB/cm)	<0.5	<0.1
Refractive index ranges	1.5-1.7	1.4-1.8
Intrinsic birefringence	<0.01	None
(dn/dT) aperture	1%	0.01%
HOST POLYMER MAIN CHAIN		
Solution Properties	**Acceptable**	**Preferred**
Viscosity, cps	800-2500	800-1500
Particle contamination	Filter, 0.2 μm	Filter, 0.2 μm
Solvent boiling point, °C	120	200
Percent solids	>15%	100%
Mechanical Properties	**Acceptable**	**Preferred**
Tensile strength (kg/mm^2)	>10	>30
Elongation to break (%)	>10	>50
Young's modulus (kg/mm^2)	>250	>1000
Barcol hardness	>70	>70
Process temperature, °C	>400	>250
Dilation modulus	TBD	TBD

[1] "Nonlinear Optical Polymers: Challenges and Opportunities in Photonics" A.F. Garito, J.W. Wu, G.F. Lipscomb and R. Lytel, Mat. Res. Soc. Symp. Proc. Vol. 173 (1990).

TABLE 18 (continued)
Materials Requirements for Integrated Optical Polymer Devices[1]
ACTIVE DEVICES

Thermal Properties	**Acceptable**	**Preferred**
CTE (ppm/°C)	<10	<10
Weight loss temp. (1%@°C)	450	550
T_g, °C	>300	>400
T_m, °C	None	None
Thermal conduction	Large as possible	Large as possible
Chemical Properties	**Acceptable**	**Preferred**
Solvent Resistance Ketones Aromatics Aromatic amines Cl, F, Alky	No cracking or weight loss	
Acid/base resistance	No cracking or weight loss	
Water absorption (100°C, 12 h)	<3%	<0.5%
Hydrolytic stability	No cracking or weight loss	
Total ionics (ppm)	<10	<1
Electrical Properties	**Acceptable**	**Preferred**
Dielectric constant	<3.5	<2.5
Dielectric constant change, wet (100°C, 12 h)	<10%	<1%
Loss tangent	<0.001	<0.0001
Dielectric strength, V/μm Room temperature Glass transition temperature	 >150 >100	 >250 >250
Volume resistivity (Ω·cm)	$>10^{16}$	$>10^{16}$
Surface resistivity (Ω·sq)	$>10^{15}$	$>10^{15}$

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[1] "Nonlinear Optical Polymers: Challenges and Opportunities in Photonics" A.F. Garito, J.W. Wu, G.F. Lipscomb and R. Lytel, Mat. Res. Soc. Symp . Proc. Vol. 173 (1990)

important for disseminating to device users the relative merits of each technology. It was recognized that for the outputs from such an exercise to be broadly adopted, it would have to be conducted as an industry/government/university cooperative program with the outputs widely distributed to U.S. concerns. Such a side-by-side benchmarking program would advance waveguide processing methods for poled polymers, promote a distributed knowledge base between disciplines and competitors on precompetitive aspects of photonic materials technologies, and translate experience and "know-how" between different industrial communities.

Table 19 lists the most salient organic electro-optic polymers technology issues and research items that were assembled by the working group.

Principal Recommendations

Specific recommendations particular to each set of materials are contained within Tables 16, 17, and 19 of this section. In addition, from these individual recommendations, common cross-cutting concerns emerged that applied to all active materials, irrespective of their material class. These cross-cutting requirements are listed below along with specific recommendations that would substantially push this technology beyond being a laboratory curiosity to becoming a commercial success.

- Stimulate development of industry-led active device benchmark technology

  Bring together suppliers, manufacturers, and users employing concurrent engineering to advance active device technology suitable for large-volume applications. Shared pre-competitive data, measurements, standards, modeling and simulation, figures-of-merit, manufacturability, and prototype device demonstration should characterize this effort.

- Promote improved $LiNbO_3$ quality

  Variability among lithium niobate vendors exist for impurity levels, nonlinear optical properties, and long-term optical durability. Develop $LiNbO_3$ standard reference material (SRM), and broadly adoptable material characterization methods suitable for laboratory accreditation.

- Benchmark polymer EO modulator with respect to $LiNbO_3$

  A neutral party should orchestrate an industry-led exercise to reference the performance, manufacturability, and economic figures-of-merit for a polymer-based electro-optic modulator to those of $LiNbO_3$. The program should involve a cross-cut of industry leaders; seek to advance needed enabling materials, processing, and manufacturing technologies; and result in an open intercomparison between the two device technologies.

TABLE 19
Issues for Electro-optic Polymers
ACTIVE DEVICES

Issues	Mat	Man	Mea
Highest Priority			
Incomplete mapping of relevant properties for candidate materials	R, SRM	G, P, S, T, W	B, C, D, E, F, MS, OL, ON, SRD, T, W
Limited understanding of interrelationships between "primary" and "secondary" material properties	N,R	P, S, W	C, DF, E, OL, ON, P, W
Lack of industry-hardened micro-fabrication technology	P, S. SRM	D, E, F, G, M, P, W	B, I, T, W
Excessive insertion losses and attenuation at 1.3 μm and 1.55 μm	N, P, R, S	D, E, F, G, M, P, W	C, DF, MS, OL, ON, P, W
Lower Priority			
Improved nonlinear optical activity	N	I, S	D, MS, OL, ON, P
Long-term durability	I, P, S		C, D, DF, F, MS, OL, ON, P
Translation of thin-film technology from semiconductor industry	R	E, G, W	D, E, W
Development of Chi-3 and photorefractive polymers	N, R	I, W	D, DF, E, MM

See Legend at bottom of Table 14 for explanations of abbreviations.

- Advance processing technologies for active materials: inorganic crystals, III-V semiconductors, and electro-optic polymers

  Advancements in enabling processing technologies are needed to translate active materials and associated device prototypes from laboratory curiosities to high-volume, lower cost production. A cooperative industry consortium - government program is recommended to accomplish this with results shared among all participants.

PASSIVE DEVICES

G. Thomas Davis, NIST

Participants

Charles T. (Tom) Walker, Discussion Leader	3M Company
Don Keck, Discussion Leader	Corning
G. Thomas Davis, Reporter	NIST
Bruce Booth	DuPont
Gary Boyd	3M
Julian Bristow	Honeywell
William Glenn	United Technologies
Narindor Kapany	Kaptron Inc.
Rudolf Kazarinov	AT&T Bell Labs
Howard Lemberg	Bellcore

Introduction

Passive devices are those which use the optical properties of materials that do not rely upon the application of an electric field. The most widely used example is the optical fiber in which light is confined for transmission. Light is confined within a fiber or planar waveguide by internal reflection at the boundary between the transmitting material and a coating material of lower refractive index. Examples of other passive devices are listed in Table 20; some of them will be briefly described below.

Splitters are devices which split the light travelling in one optical fiber into two or more equal paths. Frequently, 1 x 2 splitters are cascaded to create 4, 8, or 16 equal paths. Couplers provide the reverse function, combining light from two or more fibers into a single fiber. Their cost at the present time is rather expensive because of the low volume demand.

Corning Glass Corporation uses a process to make flat optical waveguides such as splitters and couplers in glass by first creating a mask of the desired configuration on glass by lithographic photoresist techniques common to the semiconductor industry. A region of high refractive index is created in the open regions of the mask by allowing thallium ions to diffuse in while immersed in a bath of molten salt. Several waveguides are created on a large sheet and then cut apart. Connections are made between the waveguides and optical fibers using an adhesive and the assembly is hermetically sealed as a single package with

TABLE 20
Examples of Passive Devices

Optical fibers	Connectors
Splitters	Couplers
Taps	Attenuators
Isolators	Filters
Switches	Sensors
Erbium-doped optical amplifiers	Interfaces
Wavelength division multiplexers (WDM)	

optical fibers emanating from the structure for connection to an optical fiber network. Such splitters and couplers now cost about $500.00 each.

AT&T Bell Labs have created optical waveguides of silica (SiO_2) on silicon which rely on techniques readily available in the silicon semiconductor industry. A 15 μm-thick layer of SiO_2 is oxidized on the Si surface at high temperature and pressure. This layer will become the confining cladding on the bottom of the waveguide. Next, a layer of silica about 5 μm in thickness containing 6% P (dissolved element) is uniformly deposited by chemical vapor deposition (CVD). This layer will be the guiding medium. Desired patterns are created by conventional photolithographic techniques and reactive ion etching. Finally, a 5 to 10 μm thick coating of silica containing 2% P and 2% B (dissolved element) is deposited by CVD. The final layer containing the P and B has a refractive index that matches that of the silica on the silicon substrate but has a lower glass transition temperature which permits annealing to smooth the surface. Shortcomings of the process are that refractive index differences are limited to those achieved by dopant elements common to the semiconductor industry and more than 8% P (dissolved element) cannot be achieved. It would be desirable to assemble a system for building waveguides on silicon that had more flexibility in the chemicals that can be used. For example, TiO_2-doped silica has a much larger refractive index than P-doped silica and flame hydrolysis deposition offers compositions not achievable by CVD.

The same type of devices are made by DuPont using a photosensitive acrylate polymer (which they call Polyguide^R) and Honeywell fabricates optical waveguide splitters and couplers using a polyamide and reactive ion etching. The polymeric devices also cost about $500.00. The optical losses in the polymeric devices are currently being evaluated at Bellcore. Some members of the working group indicated a need to develop measurement methods to determine optical loss in polymeric waveguides.

The list of passive devices in Table 20 includes amplifiers. Strictly speaking, amplifiers are not passive devices but they are included here because it is desirable to create ways of incorporating an optical amplifier as an integral part of passive devices to compensate for optical loss in the device. Erbium-doped, optical-fiber amplifiers operate something like a laser without the need for cavity mirrors. The erbium ions are pumped to a population-inverted excited state by a diode laser (InGaAsP at 1.48 μm in a current version). A transmitted light pulse stimulates emission from the erbium at the same wavelength of the pulse with an effective amplification of about 30 dB (i.e., 10^3). All wavelengths between 1.53 and 1.56 μm can be equally amplified. However, there is a great need for optical fiber amplifiers that operate in the vicinity of 1.3 μm, which is another commonly used wavelength.

The largest application of electro-optics in the near future is expected to be in telecommunications. At the present time, about 95% of the telephone trunk lines in the U.S. have been converted to optical fiber. As optical fibers replace copper lines in the distribution networks and eventually to the curb outside customers' homes, a huge number of splitters are going to be required. The use of optical fibers in the distribution networks and to curbside are referred to as Fiber in the Loop (FITL) and Fiber to the Curb (FTTC), respectively. It is anticipated that the demand for such passive devices will reduce their cost as facilities are created for mass production. It should be noted that experience has shown that failures are most likely to occur at fiber optic junctions. As the number of junctions increase, it becomes increasingly important to understand and overcome the reasons for such failures. Accelerated environmental testing methods must be developed.

Even though splitters are expensive, the most expensive component at the present time is the electronics required to convert the optical signals to electric signals to be carried over copper wire to the customer's telephone, television, etc.

Other areas in which growth of electro-optics is expected include the following:

- data communications
    - local area networks
    - wide area networks

- industrial applications
    - automotive
    - aerospace
    - automation control
    - commercial computers
    - biomedical

In all of these markets, the most important issues are cost and the ability to meet the customers' specifications.

One of the many advantages of using light and optical fiber transmission is that multiple channels of information can be transmitted through the fiber at the same time using light of different wavelengths. At the end of the transmission line, the wavelengths are separated using another passive device, a wavelength division multiplexer (WDM), which can be thought of as a diffraction grating or prism.

A wide variety of passive optical devices can be created from photo-induced Bragg gratings in optical fibers. W. H. Glenn of United Technologies outlined how such gratings are made, current understanding of the mechanism involved, and how they can be used in signal processing and in sensors. Using a commercially available optical fiber which is purposefully high in Ge content, one can create a grating of refractive index along the fiber by exposing it to an interference pattern created from ultraviolet light of 245 nm wavelength. One model for the origin of the photosensitivity is that an oxygen vacancy between Si and Ge is responsible for the absorption at 245 nm which gives rise to a variety of other centers. Although the resulting refractive index change is small, the large number of partially reflecting boundaries in a short length of fiber can act essentially as a mirror for selected wavelengths of light. Reflectivities of over 99% have been demonstrated in a grating of a few millimeters length. Examples of applications for Bragg gratings in signal processing from Dr. Glenn's presentation are listed in Table 21 and applications in sensors are listed in Table 22. Any stimulus which causes a change in length or refractive index of the grating should be detected.

According to Dr. Glenn, there are several areas of opportunity for research on photo induced Bragg gratings. The basic mechanism involved in the photosensitive index change is not known with certainty--only models have been proposed. In addition to germanium, europium dopants in silica cause photosensitivity but there may be many other dopants that can be used. Such dopants and the energy required to sensitize them should be sought. How can photosensitivity and possible index change be maximized? Photosensitivity depends on Ge content as well as processing history of the film; there is a need to determine and control the process variables.

TABLE 21
Applications of Bragg Gratings in Signal Processing

Narrow bandpass and bandstop filters
Fabry-Perot filters, all-fiber with high finesse
Optical pulse compressors
Wavelength multiplexers and demultiplexers
Tunable all-fiber lasers
Optical matched filters
Programmable RF delay lines
RF and optical transversal filters

TABLE 22
Applications of Bragg Gratings in Sensors

Temperature
Pressure
Strain
Acoustic fields
Magnetic fields
Electric fields
Gravitational fields

Issues

A compilation of the materials issues in passive devices is shown in Table 23. Adhesives are used in devices throughout the photonics industry. When used in the optical path, as in making the connections between optical fibers and flat optical waveguides in splitters and couplers, the adhesive must match the refractive index of the transmitting media at the wavelength being used (usually 1.3 or 1.55 μm). In all cases, it must be stable over long periods of time and exhibit a coefficient of thermal expansion (CTE) close to that of the materials being joined. The same criteria for CTE obtains for the material used to seal the devices in a package to protect them from the environment and mechanical damage.

Further knowledge of how the refractive index of materials can be changed is desired as well as a wider range of refractive index in both polymers and inorganic glasses. As indicated in Table 23, these index differences are required for constructing splitters and couplers, for creating grating filters, for packaging devices and in fiber cladding. New glasses, especially ones doped to achieve a particular refractive index, should be developed for new optical fibers.

Optical loss and the factors that control it are enormously important. It is a critical factor at all connections and in all passive devices. Absorption due to molecular vibrations in organic polymers in the 1.3 to 1.5 μm wavelength range is of special concern when developing polymeric optical fibers or polymeric waveguides. Substitution of F for H in polymer molecules was mentioned as one possible means of reducing absorption due to C-H stretching vibrations. Absorption in this region of the spectrum is another reason for wanting to prevent the intrusion of water.

In the case of optical fibers where continued development has gradually reduced optical loss over the years, chromatic dispersion has become the limiting factor in data transmission rates. It would be highly desirable to develop a material which exhibited dispersion characteristics opposite that of current optical fibers which could then be used to correct for the dispersion.

Connector ferrules were mentioned frequently during the workshop. They are widely used, are rather expensive, and are available from only one Japanese supplier. They are used for connecting two optical fibers. They are ceramic structures containing a groove in which the optical fiber fits snugly. The ends of the fibers to be connected are polished flat and held in physical contact by clamps on the connector. The photonic companies in the U.S. would like to be able to purchase connector ferrules domestically and, furthermore, they would like to see an acceptable, less expensive replacement.

TABLE 23
Materials Issues
PASSIVE DEVICES

Adhesives	Thermal expansion compatibiltiy
in optical path	packaging
out of optical path	interfaces
Wider range of refractive index	coatings
constructing splitters and couplers	Optical loss
packaging	materials
grating filters	couplings
New fibers	devices
passive	wavelength selective
polymeric	Connector ferrules
glass	replacement for ceramic
polymer coated	development of U.S. supplier
active	
amplifiers	
photorefractive	

A list of generic research needs was compiled by the working group, but no priorities were established nor were there extensive examples given under each heading. This list of needs is presented in Table 24.

Materials properties in Table 24 include refractive index and optical loss as a function of wavelength, coefficient of thermal expansion, sensitivity to moisture absorption, and uniformity of refractive index. Device characterization would also involve measurements of optical loss as a function of wavelength and characterization with respect to changes in environment such as temperature and humidity. It is expected that the future will see the

TABLE 24
Generic Research Needs
PASSIVE DEVICES

Materials characterization
Device characterization
Device and materials modelling
Adhesive/integrated optics interface
Engineerable n, dn/dT, CTE
Materials stability (including photochemical)
Compatible substrates and printed circuit boards (PCBs)
Failure mechanisms

interfacing of photonics and electronics in an integrated circuit. Substrates compatible with both should be sought as opposed to trying to make photonics conform to substrates and printed circuit boards (PCBs) developed for the electronics industry. The stability of materials when subjected to the usual effects of environment and temperature fluctuations must be addressed, but also the photochemical stability of materials subjected to the light being transmitted in the network is of prime importance. Finally, experience has shown that most failures in optical networks occur at places where fibers have been joined together or to devices such as splitters, couplers, filters, etc. It is important to understand the mechanisms of failure in order to design more reliable optical networks.

The issues discussed above have been summarized in Table 25 where they have been assigned to categories labeled materials, manufacturing, and measurement. Although no priorities were established by participants of the passive devices working group, the issues have been arranged in order of decreasing priority as seen by the reporter.

In addition to the issues presented above, the participants at the workshop discussed generic infrastructure needs. They would like to see the establishment of a data base on properties and processing conditions of photonic materials. U.S. data should be compared with data outside the U.S. and such data should be available on a network. It would be desirable to generate and disseminate specifications or standards required for the various markets for photonic materials. It would also be desirable to foster the development of a location that

TABLE 25
Major Issues

PASSIVE DEVICES

(Decreasing order of priority in each column)

Materials	Manufacturing	Measurement
Replacement for ceramic ferrules	U.S. supplier of connector ferrules	Characterization of materials for use in planar glass splitters & couplers
Optical fiber amplifiers for 1.3 μm wavelength	Reduce time and cost of glass fiber processing	Thermal expansion compatibility of optics and packaging
Material to reverse effects of chromatic dispersion	Develop new deposition techniques for fabricating optical waveguides	Environmental stability of fiber optic junctions
Adhesives for use in the optical path	Incorporate optical amplifiers in passive devices to compensate for loss	Optical loss in polymeric waveguides
New glasses, especially doped ones	PCB substrates compatible with both optics and electronics for OEICs	Failure analysis
Dopants other than Ge and Eu in silica for creation of photo induced Bragg gratings	Determine and control process variables that effect photosensitivity of doped silica	Properties of coatings
Materials with wider range of refractive index than are now available	Simplify procedure for metal organic chemical vapor deposition (MOCVD)	Improved measurement techniques for epitaxially grown structures
Adhesives for use outside the optical path		Compatibility of coatings and devices
Polymers with index matched to that of glass		

possessed the ability to perform (1) modeling of photonic systems, (2) materials characterization, and (3) device characterization and testing. With respect to the last item, device characterization and testing, many of the participants encouraged the establishment of a series of round- robin tests on devices which would respect the proprietary aspects of devices being circulated to competitor laboratories.

PACKAGING

Joseph A. Carpenter, Jr, NIST

Participants

These persons contributed substantially to the discussions of this group.

Tim Butrie, Chairman	AT&T
Joseph A. Carpenter, Jr., Reporter	NIST
Maurizio Arienzo	IBM
Roland Haitz	Hewlett Packard
Sanjiv Kamath	Hughes
Harry Lockwood	GTE Laboratories
Raj Rajasekharan	Digital Equipment Corporation /Cornell
Terry Smith	3M
Harvey Trop	AT&T
Joseph Williams	IBM

Introduction

As in electronics, packaging (meaning the materials and the assembly and testing processes) is a major part of the cost of photonic devices, as much as 75% in some cases. It also greatly influences the product performance and reliability. The packaging sophistication selected for a given application is a balance between performance, reliability, and cost, with cost being the major consideration for commercial applications.

Tim Butrie gave the keynote address on the subject of photonic packaging in the initial plenary session. Harry Lockwood, Raj Rajasekharan, Terry Smith, Harvey Trop, and Joseph Williams gave presentations during the working sessions. Contemporary workshops and studies (e.g., 1) by other organizations were noted in the discussions, thus highlighting the increasing awareness of the relative importance of packaging to commercial photonic systems.

Most of the discussions of this working group focused on laser modules and fiber connectors; some minor references were made to packaging $LiNbO_3$ used as modulators and switches. Excellent background reviews of the current state-of-the-art in laser modules and fiber connectors for commercial photonic systems are given in references 2 and 3, respectively. Figure 1, from reference 2, schematically depicts a typical laser module.

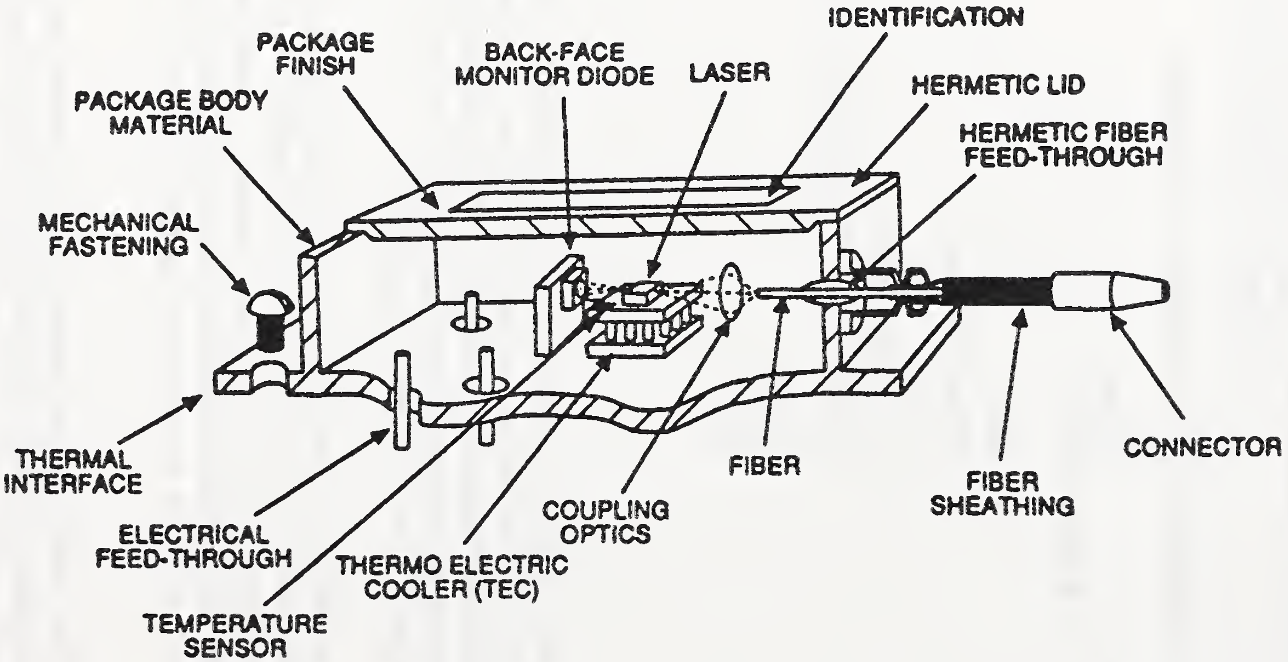

Figure 1. Schematic illustrating the major features of a typical state-of-the-art laser module. Reprinted, with permission, from reference 2.

The applications considered included long-haul telecommunications (TELECOM) and cable television (CATV), local telecommunication loops, data communications (DATACOM), and military. Though differences in the packaging needs of these applications were recognized, the working group found it did not have enough time to identify the optimal balance for the various applications and thus identified the following five generic areas of importance. The issues identified are summarized in Table 26; the relative priority of each is indicated.

Alignment and fixation of fibers to lasers or waveguides

The major difference between photonic and electronic systems is that photonic systems require about an order of magnitude tighter dimensional tolerances in the alignment of fibers or waveguides with the lasers or waveguides on the modules compared to alignment of electrical wires with bond pads. This is especially true for single-mode fibers. Not enough is known about the relative costs of the traditional active (in which the fiber is mechanically aligned with the laser activated) or the relatively newer passive (physically guided) alignment methods as functions of manufacturing volume for manufacturers to make good decisions as to which method is most cost-effective for a given product. The group discussed the possibility of some effort to obtain such information. Figure 2 provides an example of a GTE Laboratories' advanced passively aligned concept, described in detail in reference 4; a passive alignment process has also been described by IBM in reference 5.

The major materials issues are associated with the behaviors of the materials involved in permanently fixing the alignments. The three main methods used are soldering, laser welding, and adhesive bonding; soldering is the traditional method, laser welding is considered by many to be the preferred method, and adhesive bonding would be preferred (because of cost and simplicity) if it could achieve the stability of laser welding. More needs to be known about the behaviors of the materials (e.g., distortion, creep, relaxation) during the fixation process, during subsequent testing, and over the lifetime of the product.

Coupling efficiency was also discussed, but no clear consensus was achieved (see reference 2, especially Figure 6 therein, for background). While efficiencies higher than the 10-20% of simple butt coupling would be attractive, the more important aspect is that the coupling be stable as possible in efficiency and noise. Studies of ways of achieving such stability at lowest cost were suggested.

Precision, low-cost materials for connectors

Next to alignment, the second priority area is the connectors that mate the external fibers and perhaps electrical wires to one another and the enclosures that contain the photonic circuits. The connectors need to be of high dimensional precision but as low cost as possible. Low-cost processes for producing ceramic ferrules (see reference 3 for background) with a variety of shapes, yet having very precise dimensions and surface finishes, are needed. Rapid and low-cost techniques for inspecting and precisely measuring the dimensions of such small

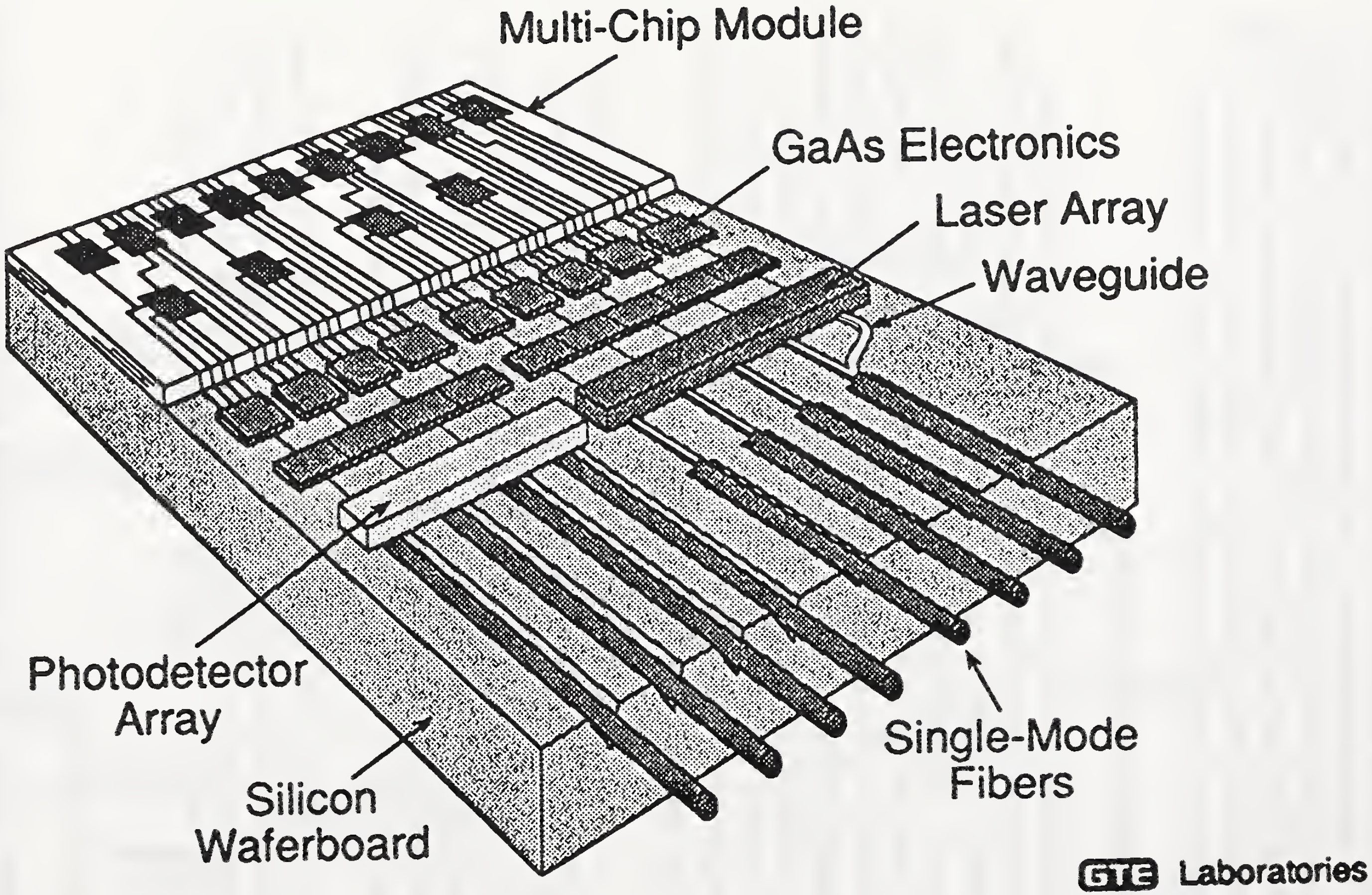

Figure 2. Schematic of GTE Laboratories' advanced multifiber transmitter/receiver concept utilizing passive alignment of fibers in etched grooves in a silicon substrate. Figure supplied by H. F. Lockwood. See reference 4 for further information.

components need to be developed. Their durability in service should be assessed and the factors affecting the durability identified.

Connector sizes and shapes should also be standardized. The ultimate development of a universal connector covering simplex, duplex and array connection is desired for future generation systems.

Packaging enclosure materials

The active devices in photonic devices are composed of materials that are as or more sensitive to environmental degradation than those in electronic devices, so photonic circuits are almost always sealed in expensive hermetic enclosures. New "passivating materials" and techniques for applying them are needed to either complement the protective capability missing in less expensive enclosures or provide all the protection needed, thus eliminating the enclosure entirely. There was discussion about the longing for an ideal material (termed the "holy glue" in analogy to the Arthurian quest for perfection) that could provide an optimal set of passivation, refractive index-coupling, low thermal expansion, high thermal conductivity and other important properties; one such set is shown in Table 27. Improvements are especially needed to lower the cost and increase the reliability of single and array optical feed-thrus of the enclosures.

Substrates

Photonic circuits are mounted on a variety of ceramic, semiconductor (mostly Si), metal, and polymeric substrates which primarily provide mechanical support and heat removal. More needs to be known about the dimensional and chemical stabilities of the substrate materials during processing, testing and over life in service. Two other properties of major interest are coefficient of thermal expansion (CTE) and thermal conductivity, the latter being particularly important in higher power systems. Of special concern to systems experiencing high temperatures is the tendency of certain metallizations and solder to disappear from porous ceramic substrates as result of lift-off or even dissolution.

Modeling

Improved capabilities for simulating the optical performances of photonic circuits, connections and feed-thrus are needed. Good three-dimensional (3D) computer models would be used to verify the accuracies of simpler one- and two-dimensional models now used. These 3D models would be especially useful in determining just how close the tolerances have to be and how they might vary in-service especially as result of temperature changes. Finally, in order for the models to produce reliable results, there is a need for an improved database of material properties, particularly those of passive waveguides and discrete coupling lenses.

TABLE 26

Summary of Issues Identified

PACKAGING

Issues	Mat	Man	Mea
Alignment and Fixation of Fibers to Lasers or Waveguides (High)			
Understanding relative costs of active versus passive alignment methods as functions of manufacturing volume.		x	
Behaviors of the alignment materials during the fixation process, subsequent testing, and over the lifetime of the product.	x		
Achieving maximum coupling efficiency and stability of connectors at lowest cost.		x	
Precision, Low-Cost Materials for Connectors (Medium)			
Low-cost processes for producing ceramic ferrules with a variety of shapes yet having very precise dimensions and surface finishes.		x	
Rapid and low-cost techniques for inspecting and precisely measuring the dimensions of such small components.		x	x
Assessment of their durability in service and identification of the factors affecting the durability.	x		
Standardization of connector sizes and shapes.		x	
Ultimate development of a universal connector covering simplex, duplex and array connection.		x	

TABLE 26 (Continued)
Summary of Issues Identified
PACKAGING

Issues	Mat	Man	Mea
Packaging Enclosure Materials (Medium)			
New "passivating materials" and techniques for applying them.		x	
Development of an ideal material ("holy glue") that could provide an optimal set of properties.	x		
Lowering the cost and increasing the reliability of single and array optical feed-thrus.			
Substrates (Medium)			
Better understanding the dimensional and chemical stabilities of the substrate materials during processing, testing and over life in service.	x		
Better measurements for and understanding of factors affecting coefficient of thermal expansion (CTE) and thermal conductivity.	x		x
Understanding the disappearances from ceramic substrates of certain metallizations and solder.	x		
Modeling (Low)			
Development of three-dimensional computer models for predicting the optical performances of photonic circuits, connections and feed-thrus in order to verify the accuracies of simpler one- and two-dimensional models now used.		x	
Improved database of material properties, particularly those used in passive waveguides and discrete coupling lenses.	x		

TABLE 27
"The Perfect Adhesive"
(according to Terry L. Smith, 3M)

Would have the following characteristics:
• Strong
• Flexible to accommodate thermal expansion
• Does not creep
• Sticks to everything without "flux"
• Low viscosity
• Cures fast at room temperature (< 1 min.)
• Cure does not require complete illumination
• Does not change specific volume at cure
• Long pot life
• No outgassing
• Usable from -40 to + 80°C
• Easily removable for rework
And Maybe -
• Optically transparent from visible to 1.5 μm
• Index matched to optical fiber
• Thermal expansion tunable 1-30 ppm/°C

Breakthroughs

In addition to the above, two topics were identified as the most desired breakthroughs in packaging for photonic systems. First, a strong U.S. photonic packaging infrastructure is very much desired. Second, a perfect encapsulant ("holy glue," see above) is sought.

References

1. L. K. Anderson, W. T. Cathey, S. Fainman, H. S. Hinton, S. Kang, J. F. McDonald, A. J. Maltenfort, and R. C. Mercure, Jr., "Report to the NSF on Optoelectronic Packaging Workshop," held in Boulder, CO, August 1 and 2, 1992. (September 1991).

   L. Anderson, Y. C. Lee, A. Mickelson and Z. Popovic, "A Report to the NSF on The Symposium on Optoelectronic Packaging Science," held in Estes Park, Colorado, August 19-21, 1992 (November 1992).

   In addition, there was a session "Optoelectronic Packaging" on August 27, 1992, during the 7th Electronic Materials and Processing Congress sponsored by ASM International in Cambridge, MA; and a workshop/conference "Challenges in Optoelectronic Packaging," jointly sponsored by the Components, Hybrids and Manufacturing Technology (CHMT) Society and the Lasers and Electro-Optics Society (LEOS) of the Institute of Electrical and Electronic Engineers (IEEE), was held September 30-October 1, 1992, in Baltimore, MD.

2. D. S. Alles, "Trends in Laser Packaging," 1990 Proceedings of the 40th Electronic Components and Technology Conference, Las Vegas, NV, May 20-23, 1990 (Institute of Electrical and Electronic Engineers, New York, NY, 1990), pp. 185-192.

3. B. G. LeFevre, "Materials in Fiber Optic Connections," Materials Developments in Microelectronic Packaging Performance and Reliability, P. Singh, ed. (ASM International, Materials Park, OH, 1991), pp. 215-223.

4. C. A. Armiento, A. J. Negri, M. J. Tabasky, R. A. Boudreau, M. A. Rothman, T. W. Fitzgerald, and P. O. Haugsjaa, "Four-Channel, Long-Wavelength Transmitter Arrays Incorporating Laser/Singlemode-Fiber Alignment on Silicon Waferboard," 1992 Proceedings of the 42nd Electronic Components and Technology Conference, San Diego, CA, May 18-20, 1992 (Institute of Electrical and Electronic Engineers, New York, NY, 1992), pp. 108-114.

5. M. S. Cohen, M. F. Cina, E. Bassous, M. M. Oprysko, J. L. Speidell, F. J. Canora, and M. J. Defranza, "Packaging of High-Density Fiber/Laser Modules Using Passive Alignment Techniques," 1992 Proceedings of the 42nd Electronic Components and Technology Conference, San Diego, CA, May 18-20, 1992 (Institute of Electrical and Electronic Engineers, New York, NY, 1992), pp. 98-107.

PROGRAM
Photonic Materials Workshop
Lecture Room A/Administration Building

Day One - Wednesday, August 26, 1992

8:00 am	Registration	
8:30 am	Introduction	Steve Freiman, Workshop Chairman Acting Chief, Ceramics Division
8:35 am	Welcome	Lyle Schwartz Director, Materials Science and Engineering Laboratory, NIST
8:40 am	Introductory Remarks	Roland Haitz, Optoelectronics Industry Development Association
8:45 am	The Japanese Vision of the Optoelectronics Industry	Mark Chandler, Hewlett Packard
9:15 am	Semiconductors	Roland Haitz, Hewlett Packard
9:45 am	Semiconductors	Sanjiv Kamath, Hughes
10:15 am	Break	
10:30 am	Ceramics and Glasses	Alastair Glass, AT&T Bell Labs
11:00 am	Polymers	Bruce Booth, Dupont
11:30 am	Polymers	Hyun-Nam Yoon, Hoechst Celanese
12:00 pm	Packaging	Tim Butrie, AT&T Bell Labs
12:30 pm	Displays	Malcolm Thompson, Xerox
1:00 pm	Lunch - Senior Lunch Club Presentation on the NIST Advanced Technology Program - George Uriano, Director, ATP	
2:00 pm	Working Groups - Parallel Sessions	Working Group Leaders
	Sources and Detectors - Lecture Room A	Bob Leheny, Bellcore
	Storage - A366/Physics	Gary Bjorklund, IBM
	Active Devices - B307/Materials	Adrian Popa, Hughes
4:00 pm	Break	
4:15 pm	Working Groups - Parallel Sessions	Working Group Leaders
	Displays - L. R. A	Malcolm Thompson, Xerox
	Passive Devices - B307/Materials	Tom Walker, 3M Donald Keck, Corning
	Packaging - A366/Physics	Tim Butrie, AT&T Bell Labs
6:15 pm	Adjourn for the Day	
6:20 pm	Bus returns to Gaithersburg Marriott	
6:45 pm	Reception and Banquet, Marriott Salons D and E	
8:15 pm	After Dinner Speaker	Robert White Undersecretary for Technology

Day Two - **Thursday, August 27 1992**

8:30 am Working Groups, Preparation of Preliminary Reports

* Six Concurrent Group Meetings (see below for locations)

10:00 am Break

10:15 am Plenary Session, Preliminary Reports of Working Groups and Discussion - L.R. A

12:00 pm Lunch - Main Cafeteria

12:45 Plenary Session, Discussions of Preliminary Reports and Ways of Implementating Recommendations - L. R. A

2:30 pm Break

2:45 pm Working Groups - Further Revision of Reports

* Six Concurrent Group Meetings (see below for locations)

4:30 pm Wrap-up - Working Group Leaders and NIST Personnel

5:30 pm Adjourn Workshop

** Working Group Meeting Locations --*

Sources and Detectors	*Lecture Room A*
Storage	*A366/Physics*
Active Devices	*B111/Admin.*
Displays	*B267/Materials*
Passive Devices	*A258/Materials*
Packaging	*B113/Admin.*

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NIST/OIDA Photonic Materials Workshop Steering Committee

Maurizio Arienzo, IBM
Marc Brodsky, IBM
Joseph Carpenter, Jr., NIST
Jack Chang, Kodak
Gordon Day, NIST
John Day, Strategies Unlimited/OIDA
Albert Feldman, NIST
Stephen Freiman, NIST
Alastair Glass, AT&T
Roland Haitz, Hewlett Packard
Anis Husain, Honeywell
Robert Leheny, Bellcore
William Ott, NIST
Alan Pine, NIST
Richard Reynolds, Hughes
Aaron Sanders, NIST
Michael Schen, NIST
Charles T. (Tom) Walker, 3M

Thank you from NIST and the OIDA.

Final Participants List

NIST/OIDA Photonic Materials Workshop
National Institute of Standards and Technology
Gaithersburg, MD

August 26-27, 1992

Bill Ahlgren
Hughes Research Ctr.
75 Coromar Drive
Bldg. B2/MS-55
Goleta, CA 93177
805/562-2180

Paul Amirtharaj
NIST
Bldg. 225, Rm. B305
Gaithersburg, MD 20899
301/975-5974

Maurizio Arienzo
IBM Corp.
TJ Watson Research Ctr.
P.O. Box 218
Yorktown Heights, NY 10598
914/945-3561

William Randall Babbitt
Boeing Aerospace & Elec.
P.O. Box 3999 MS 7J-91
Seattle, WA 98124
206/865-3307

Nadav Bar-Chaim
Ortel Corp.
2015 W. Chestnut St.
Alhambra, CA 91803
812/281-3636

John Batey
IBM Corp.
TJ Watson Research Ctr.
P.O. Box 218
Yorktown Heights, NY 10598
914/681-5545

Herbert Bennett
NIST
Bldg. 220, Rm. B358
Gaithersburg, MD 20899
301/975-2079

Gary Bjorklund
IBM Almaden Research Ctr.
Dept. K95-801
650 Harry Rd.
San Jose, CA 95120
408/927-2424

Bruce Booth
DuPont Company
P.O. Box 80357, Bldg. 357
Experimental Station
Wilmington, DE 19880-0357
302/695-3050

Gary Boyd
3M Center
201-2N-19
St. Paul, MN 55144
612/736-7232

Julian Bristow
Honeywell
10701 Lyndale Ave.
MN09-D200
Bloomington, MN 55420
612/887-4023

Tim Butrie
AT&T Bell Lab.
9999 Hamilton Blvd.
Room 2E236
Breiningsville, PA 18031
215/391-2743

Paul Carey
Lawrence Livermore Natl. Lab.
P.O. Box 503, L-271
Livermore, CA 94551-9900
510/422-4424

Joseph Carpenter
NIST
Bldg. 223, Rm. A257
Gaithersburg, MD 20899
301/975-6397

Mark Chandler
Hewlett Packard
370 W. Trimble Rd.
MS 91MG
San Jose, CA 95131
408/435-6017

Lap-Tak Cheng
DuPont
P.O. Box 80356
Wilmington, DE 19880
302/695-9256

Sandra Collins
AstroPower
Solar Park
Newark, DE 19716
302/366-0400

Herbert Cox
Bellcore
331 Newman Springs
Redbank, NJ 07701
908/758-3383

Charles Cox
MIT Lincoln Lab.
MS C337
244 Wood St.
Lexington, MA 02173
617/981-4519

Chris Cromer
NIST
Bldg. 221, Rm. A221
Gaithersburg, MD 20899
301/975-3216

William Dautremont-Smith
AT&T Bell Labs.
600 Mountain Ave., Rm 2C-318
Murray Hill, NJ 07976
908/582-7667

G. Thomas Davis
NIST
Bldg. 224, Rm. B320
Gaithersburg, MD 20899
301/975-6725

John Day
Strategies Unlimited
201 San Antonio Cir.
Suite 205
Mountain View, CA 94040
415/941-3438

Gordon Day
NIST
325 Broadway
814.02/Rm. 3063
Boulder, CO 80303
303/497-5204

Bruno Fanconi
NIST
Bldg. 224, Rm. A309
Gaithersburg, MD 20899
301/975-5762

Albert Feldman
NIST
Bldg. 223, Rm. A257
Gaithersburg, MD 20899
301/975-5740

Douglas L. Franzen
NIST
325 Broadway
Boulder, CO 80303
303/497-3346

Stephen Freiman
NIST
Bldg. 223, Rm. A257
Gaithersburg, MD 20899
301/975-6119

Judson French
NIST
Bldg. 220, Rm B358
Gaithersburg, MD 20899
301/975-2220

Anthony F. Garito
Univ. of Pennsylvania
209 S. 33rd St.
Dept. of Physics
Philadelphia, PA 19104
215/898-5810

Alastair Glass
AT&T Bell Lab.
Room 1A-164
600 Mountain Ave.
Murray Hill, NJ 07974
908/587-2463

William H. Glenn
United Technologies Research
411 Silver Lane, MS 92
E. Harford, CT 06108
203/727-7411

Claude Gravatt
Dept. of Commerce
HCHB Bldg., Rm 4841
Washington, DC 20008

Roland Haitz
Hewlett Packard
370 W. Trimble Rd.
San Jose, CA 95131
408/435-6202

Jan L. Hall
NIST
325 Broadway
JILA
Boulder, CO 80303
303/497-3126

Jonathan Hardis
NIST
Bldg. 220, Rm. B306
Gaithersburg, MD 20899
301/975-2373

Heidi Hoffman
DOC ITA
14th & Constitution Ave., NW
HCHB 1104
Washington, DC 20008
202/377-2053

Debra Kaiser
NIST
Bldg. 223, Rm. A329
Gaithersburg, MD 20899
301/975-6759

G. Sanjiv Kamath
Hughes Research Lab.
3011 Malibu Canyon, RL-92
Malibu, CA 90265
310/317-5210

Narindor Kapany
Kaptron Inc.
2525 East Bayshore
Pal Alto, CA 94303
415/493-8008

Rudy Kazarinov
AT&T Bell Lab.
Room 7B-202
600 Mountain Avenue
Palo Alto, CA 94303-3281
908/582-2106

Don Keck
Corning Inc.
SP FR 2 9
Corning, NY 14831
607/974-3095

Freddy Khoury
NIST
Bldg. 224, Rm. A209
Gaithersburg, MD 20899
301/975-6753

Robert Leheny
Bellcore
NVC 3Z-377
331 Newman Springs Rd.
Red Bank, NJ 07701-7040
908/758-3203

Howard Lemberg
Bellcore
445 South St.
Rm. 2M289
Morristown, NJ 07962
201/829-4938

Wilfred Lenth
IBM
650 Harry Rd., K69/803
San Jose, CA 95120
408/927-2029

Kurt Linden
Spire Corp.
1 Patroits Park
Bedford, MA 01730
617/275-6000

Harry F. Lockwood
GTE Laboratories Inc.
40 Sylvan Rd.
Waltham, MA 02254
617/466-2786

Louis Lome
DD/SDIO/IS&T
Pentagon, Rm. 1E167
Washington, DC 20301
703/693-1671

Gabrielle Long
NIST
Bldg. 223, Rm. A257
Gaithersburg, MD 20899
301/975-5975

Tom Long
American Display Consort.
1785 Southwest 89th Ave.
Portland, OR 97225
503/292-0380

Masud Mansuripur
Univ. of Arizona
Optical Science Ctr.
Rm. 638
Tucson, AZ 85721
602/621-4879

Mark McCollum
NIST
325 Broadway
Boulder, CO 80303
303/497-5167

Jim McNeely
AstroPower Inc.
Solar Park
Newark, DE 19716
302/366-0400

Peter Mills
Xerox PARC
3333 Coyote Hill Rd.
Palo Alto, CA 94304
415/812-4520

Ronald L. Moon
Hewlett-Packard Labs
3500 Deer Creek Rd.
Rm. 26M
Atherton, CA 94027
415/857-4673

Dale Murray
Kaptron
2525 East Bayshore
Palo Alto, CA 94303
415/493-8008

David Myers
Sandia National Labs
1515 Eubank, SE
Albuquerque, NM 87185
505/845-9563

Tom O'Neill
Bangap Technology
325 Interlocken Pkwy.
Broomfield, CO 80021
303/460-0700

Frank Oettinger
NIST
Bldg. 225, Rm. B344
Gaithersburg, MD 20899
301/975-2054

William Ott
NIST
Bldg. 221, Rm. B160
Gaithersburg, MD 20899
301/975-3038

Stephen Palfrey
David Sarnoff Research Ctr.
201 Washington Rd., SW-330
Princeton, NJ 08540
609/734-2543

Albert Parr
NIST
Bldg. 220, Rm. B306
Gaithersburg, MD 20899
301/975-2316

Joseph Pellegrino
NIST
Bldg. 225, Rm. A305
Gaithersburg, MD 20899
301/975-2123

Robert J. Phelan
NIST
325 Broadway
Boulder, CO 80303
303/497-3696

Alan Pine
NIST
Bldg. 221, Rm. B266
Gaithersburg, MD 20899
301/975-2376

Ross Pollack
American Display
Consortium/Plasmaco
180 South St.
Highland, NY 12528
914/255-4378

Paras Prasad
SUNY at Buffalo
Dept. of Chemistry
Buffalo, NY 14214
716/829-3026

Raj Rajasekharan
Digital Equipment Corp.
408 Phillips Hall
Cornell Univ., EE Dept.
Ithaca, NY 14853
607/255-7682

Steven Rolston
NIST
Bldg. 221, Rm. A167
Gaithersburg, MD 20899
301/975-6581

Aaron Sanders
NIST
325 Broadway
814.02/Rm. 3063
Boulder, CO 80303
303/497-5341

Michael Schen
NIST
Bldg. 101, Rm. A1000
Gaithersburg, MD 20899
301/975-6741

Lyle Schwartz
NIST
Bldg. 223, Rm. B309
Gaithersburg, MD 20899
301/975-5658

Terry L. Smith
3M/Fiber Optics Lab.
3M Center
Bldg. 260-5B-08
St. Paul, MN 55144
612/733-5674

Bruce Steiner
NIST
Bldg. 223, Rm. A257
Gaithersburg, MD 20899
301/975-5977

Wolfgang Stutius
Polaroid Corp.
21 Osborn Street
Cambridge, MA 02139
617/577-3262

Malcolm Thompson
Xerox PARC
3333 Coyote Hill Rd.
Palo Alto, CA 94304
415/812-4561

Harvey Trop
AT&T Bell Lab.
9999 Hamilton Blvd.
2G-204
Breinigsville, PA 18031
215/391-2817

Yuan-Sheng Tyan
Eastman Kodak Co.
Research Lab B-81
MC 02017
Rochester, NY 14650
716/477-7884

Robert Uhrin
Deltronic Crystal Ind.
60 Harding Ave.
Dover, NJ 07801
201/361-2222

George Uriano
NIST
Bldg. 101, Rm. A402
Gaithersburg, MD 20899
301/975-5187

Charles T. (Tom) Walker
3M Company
3M Center
201-2S-05
St. Paul, MN 55144
612/736-9815

Francis Wang
NIST
Bldg. 224, Rm. B320
Gaithersburg, MD 20899
301/975-6726

David Welch
Spectra Diode Labs
80 Rose Orchard Way
San Jose, CA 95134
408/943-9411

Robert White
Dept. of Commerce
HCHB Bldg., Rm. 4824
Washington, DC 20230
202/377-1575

Jerry Willenbring
Tamarack Storage Devices
3500 W. Balcones Ctr.
Austin, TX 78759
512/338-3456

Joseph Williams
IBM
9500 Godwin Dr.
MS 110-86
Manassas, VA 22110
703/367-4907

Andrew Yang
ARPA
3701 N. Fairfax Dr.
Arlington, VA 22030
703/693-2279

Huan-Wun Yen
Hughes Research Lab.
3011 Malibu Canyon
RL67
Malibu, CA 90265
310/317-5844

Hyun-Nam Yoon
Hoechst Celanese Corp.
86 Morris Ave.
Summit, NJ 07901
908/522-7786