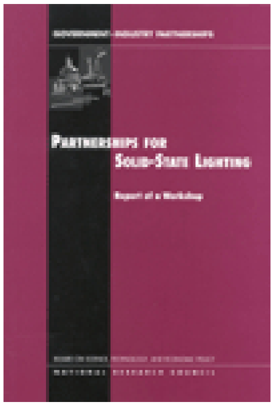

Partnerships for Solid-State Lighting: Report of a Workshop

Charles W. Wessner, Editor, National Research Council

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Partnership for Solid-State Lighting

Report of a Workshop

Charles W. Wessner, Editor

Board on Science, Technology, and Economic Policy

Policy and Global Affairs

National Research Council

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Contents

Preface

The Board on Science, Technology, and Economic Policy (STEP) of the National Academy of Sciences has under way a major review of the policy issues associated with public-private partnerships. Led by Gordon Moore, Chairman Emeritus of Intel Corporation, and a distinguished multidisciplinary *Steering Committee*,[1] analysis has taken a pragmatic, policy-oriented approach to Government-Industry Partnerships for the Development of New Technologies. Topics taken up include the drivers of cooperation among industry, government, and universities, operational assessments of current programs, emerging needs at the intersection of biotechnology and information technology, the current experience of foreign government partnerships, and the changing roles of government laboratories, universities, and other nonprofit research organizations.

On March 26, 2001, with the encouragement of the Department of Energy, the Committee organized a one-day symposium to explore the opportunities offered by and challenges faced by government-industry partnerships in solid-state lighting. The Department of Energy had earlier worked together with the Optoelectronics Industry Development Association (OIDA) to set out a technology roadmap of government-industry collaboration to advance technologies in Light Emitting Diodes, Organic Light Emitting Diodes, and other solid-state lighting sources. Participants at the workshop included experts from the lighting industry, national laboratories, universities, Congress, the National Institute of Standards and Technology, and other federal agencies.

[1]The members of the Steering Committee are listed in the front matter of this volume.

A distinguishing feature of the Committee's analysis is its desire to bring to bear the Committee's extensive assessment of U.S. partnerships on current policy questions, including emerging opportunities for public-private partnerships. Accordingly, the project has more recently focused on two areas of current policy interest.

The first area of inquiry, and a major concern of the Committee, addressed the steady declines in support for information technologies and the absence of the collaborative activities necessary to capitalize on the nation's investment in biotechnology. The Committee recommended a series of measures, in particular, enhanced support for information technologies and greater university-based collaboration across disciplinary boundaries.[2]

A second area of focus, and the topic of this report, is designed to address several interrelated questions. The first concerns the benefits offered by solid-state lighting. The second related question concerns the identification of the technical and other challenges impeding widespread market acceptance of solid-state lighting. Lastly, the report focused on what role, if any, a consortium might play in addressing these common challenges in order to bring genuine benefits of this promising technology to future generations.

PROJECT PARAMETERS

It is important to underscore that this review of the opportunities and challenges affecting the development of solid-state lighting is part of a broader review of government-industry partnerships. The Committee's analysis of partnerships has included a significant but necessarily limited portion of the variety of cooperative activity that takes place between the government and the private sector.[3] The Committee's desire to carry out an analysis of current partnerships that is directly relevant to contemporary policy making has conditioned the selection of the specific programs reviewed. The Committee also recognizes the importance of placing each of the studies in the broader context of U.S. technology policy, which continues to employ a wide variety of ad hoc mechanisms developed through the government's decentralized decision-making and management process. To meet its objective of policy-relevant analysis, the Committee has focused on the assessment of current and proposed programs, drawing on

[2]See National Research Council, *Capitalizing on New Needs and New Opportunities, Government-Industry Partnerships in Biotechnology and Information Technology,* C. Wessner, editor, Washington, D.C.: National Academy Press, 2002.

[3]For example, DARPA's programs and contributions have not been reviewed. For an indication of the scope of cooperative activity, see C. Coburn and D. Berglund, *Partnerships: A Compendium of State and Federal Cooperative Technology Programs,* Columbus, OH: Battelle Press, 1995; and the RaDiUS database, <www.rand.org/services/radius/>.

the experience of previous U.S. initiatives, foreign practice, and emerging areas resulting from federal investments in advanced technologies.[4]

The Committee's analysis is divided among four primary areas. These are current U.S. partnership programs, potential U.S. partnership programs, industry-national laboratory partnerships, and international collaboration and benchmarking. The analysis of current U.S. partnerships has focused on the Small Business Innovation Research Program, the Advanced Technology Program, and partnerships in Biotechnology and Computing. The industry-laboratory analysis has reviewed the potential and assessed policy challenges of science and technology parks at Sandia National Laboratories and the NASA Ames Research Center.

Based on the project's extensive generic partnership analysis, the Committee has also reviewed potential partnerships for specific technologies. The Committee has devoted substantial attention to the need for greater collaboration in biotechnology and computing[5] and, in this volume, opportunities for solid-state lighting. The Committee has also focused on international collaboration and benchmarking. This has included a wide review of new opportunities resulting from the U.S.-EU Science and Technology Agreement and the documentation and review of regional and national programs to support the semiconductor industry, focusing on programs in Japan, Europe, Taiwan, and the United States. The need to collaborate in addressing common challenges, even as national technology programs support competing firms, is an overarching theme of the Committee's analysis.

In general, the Committee's analysis of partnerships has focused its attention on the operation of partnerships and on how to make them more effective. Given this pragmatic orientation, the study did not (and was not intended to) take up the issue of whether partnerships should exist (they do), nor was the study designed to make comparisons between different partnership programs. Although interrelated, the studies were self-contained and did not address the question of optimal allocation of funding among programs. Practical policy relevance has been a guiding principle.

There is broad support for this type of objective analysis among federal agencies and the private sector. Among the federal agencies that provided support for this analysis are the U.S. Department of Defense, the U.S. Department of Energy, the National Science Foundation, the National Institutes of Health (espe-

[4]The Committee has focused its attention on the "best practices" rather than the practices of less successful partnerships—although it is certainly true that much can be learned from failures as well as successes. For an analysis of lessons that might be learned from comparing the experience of a less successful and a successful partnership, see John B. Horrigan, "Cooperating Competitors: A Comparison of MCC and SEMATECH." Monograph, Washington, D.C.: National Research Council.

[5]See National Research Council, *Capitalizing on New Needs and New Opportunities: Government-Industry Partnerships in Biotechnology and Information Technologies, op. cit.*

cially the National Cancer Institute and the National Institute of General Medical Sciences), the National Aeronautics and Space Administration, the Office of Naval Research, and the National Institute of Standards and Technology. Sandia National Laboratories and the Electric Power Research Institute (EPRI) have also provided important contributions. Support has also come from a diverse group of ten private corporations.[6]

ACKNOWLEDGMENTS

The STEP Partnerships project's symposium on solid-state lighting included remarks by Karen Brown, Acting Director of the National Institute of Standards and Technology, Al Romig, Vice President of Sandia National Laboratories, William Spencer, Chairman Emeritus SEMATECH, and by Arpad Bergh, President of the Optoelectronics Industry Development Association. A complete list of participants is included in Appendix A. The "Proceedings" section contains summaries of their presentations and discussions.

Given the quality and the number of presentations, summarizing the symposium proceedings has been a challenge. We have made every effort to capture the main points of the presentations and the ensuing discussions. We apologize for any inadvertent errors or omissions.

Several members of the STEP staff deserve recognition for their contributions to the preparation of this report. Without their collective effort, the production of the report would not have been possible. Alan Anderson and Sujai Shivakumar prepared initial draft manuscripts, contributed to the research required to place in context the topics raised in the meeting, and in the case of Sujai Shivakumar and Christopher Hayter, assisted in the Academies' review process. David E. Dierksheide and McAlister Clabaugh played an instrumental role in organizing the symposium under a tight deadline amidst other competing priorities and, with Christopher Hayter, prepared the manuscript for publication.

NATIONAL RESEARCH COUNCIL REVIEW

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity and evidence. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

[6]The complete list of sponsors is listed in the front matter of this report.

We wish to thank the following individuals for their review of this report:

Peter J. Delfyett, University of Central Florida
Daniel Doxee, GELcore LLC
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Nadarajah Narendran, Rensselaer Polytechnic Institute
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Charles V. Shank, E. O. Lawrence Berkeley National Laboratories

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. The review of this report was overseen by Gerald Dinneen, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

STRUCTURE

The "Introduction" in Part I of this report presents an overview of the needs and opportunities in solid-state lighting as presented at the symposium. Part II summarizes the conference proceedings, setting out in some detail the views of the symposium participants.

The goal of the workshop was to advance our understanding of the new needs and opportunities arising in solid-state lighting technology and to ensure timely consideration of policies that might encourage the development this promising technology.

I

INTRODUCTION

Introduction

Thomas Alva Edison's 1889 invention of the first commercially practical incandescent bulb continues to light the public's imagination of the brilliant but lone innovator working long hours in the laboratory. Edison is credited with inventing a better filament as well as an improved vacuum seal around this incandescent material. Today, we recognize Edison's bulb as a "disruptive technology,"[1] one that not only upset traditional lighting customs[2] but also created the power industry. Indeed, it has transformed how people the world over live and work.

Yet, Edison was not the first to invent the incandescent bulb; some 20 groups had worked for 40 years to develop a brighter and more reliable light bulb before Edison's eventual success.[3] Edison's genius, in retrospect, lay more in develop-

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[1]See Clayton Christensen, Thomas Craig, and Stuart Hart, "The Great Disruption," *Foreign Affairs* 80(2): 80-95, 2001. The authors argue that a key reason national economies rise and fall is their ability to nurture disruptive technologies. These innovations lead to new classes of cheaper and more efficient products than their predecessors. They relate the United States' ability to exploit such disruptions to its recent robust economic performance.

[2]The introduction of electric light is one milestone in the long history of disruptive technologies in lighting—from the domestication of fire by *Australopithecus,* to the use of oil lamps and candles, and beyond. For an economist's perspective on the history of lighting, see William E. Nordhaus, "Do Real Output and Real Wage Measures Capture Reality? The History of Lighting Suggests Not," in Timothy F. Bresnahan and Robert J. Gordon (eds.), *The Economics of New Goods*, vol. 58, Chicago: University of Chicago Press, 1997, pp. 29-70.

[3]In 1860, an English physicist and electrician, Sir Joseph Wilson Swan, produced his first experimental light bulb using carbonized paper as a filament. Unfortunately, Swan did not have a strong enough vacuum or sufficiently powerful batteries and his prototype did not achieve complete incandescence. See Kenneth R. Swan, *Sir Joseph Swan and the Invention of the Incandescent Electric Lamp,* London: British Council, 1948.

ing his vision of an electrical supply system—involving a grid of generators, transmitting wires, etc.—to produce and provide the power to light his bulbs for practical use.[4] This vision took time to realize; Edison's bulbs did not enter widespread use until the 1920s. Their acceptance required, among other things, the development of new manufacturing techniques, the standardization of the common bulb and socket, and the construction of a power production and distribution infrastructure.[5]

As with Edison's incandescent bulb, realizing the full potential of solid-state lighting technology will take vision. Today's solid-state lighting technology already illuminates the NASDAQ billboard in New York's Times Square. However, to realize the broader energy savings and environmental benefits, solid-state lighting technology must first come into widespread use. Mass-market acceptance of solid-state lighting involves reduced costs and improved ease of use and practicality in common applications. For widespread adoption of this technology to occur common standards will need to be developed on sockets, electrical supplies, and control interfaces.[6]

To achieve these common objectives, some form of cooperation is necessary. One approach would be to encourage further cooperative research among universities, government laboratories, and private research centers as a cost-effective means of expediting this development and encouraging additional research and collaboration on industry standards.[7] With this objective in mind, a National Academy of Sciences report recommends a national initiative in lighting. (See Box A.) This workshop report builds on this previous analysis and highlights a

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[4]The role of venture capital in Edison's research is worth noting. The Edison Electric Light Co. was formed on November 15, 1878, with the backing of financiers, including J.P. Morgan and the Vanderbilts, to carry out experiments with electric lights and to control any patents resulting from them. In return for handing over his patents to the company, Edison received a large share of stock. To capture the benefits of this invention, Edison attempted not only to devise an incandescent bulb but also an entire electrical lighting system that could be supported in a city. See <http:homestead.juno.com/pdeisch/files/bulb/htm>. Accessed December 12, 2001.

[5]See Paul A. David, "The Hero and the Herd in Technological History: Reflections on Thomas Edison and the Battle of the Systems," *Stanford Center for Economic Policy Research Discussion Paper* 100, July 1987. Also see Patrick McGuire, Mark Granovetter, and Michael Schwartz, "Thomas Edison and the Social Construction of the Early Electricity Industry in America," in Richard Swedberg (ed.), *Explorations in Economic Sociology*. New York: Russel Sage Foundation, 1993, pp. 213-46.

[6]The Energy Star program of the U.S. Environmental Protection Agency and U.S. Department of Energy is intended to encourage the use of more energy efficient products. See www.energystar.gov.

[7]Various types of risks, related to technical and commercial factors, can inhibit individual enterprises from engaging in R&D activities. For a discussion, see Albert Link, "Public/Private Partnerships as a Tool to Support Industrial R&D: Experiences in the United States." Paper presented for the OECD Committee for Scientific and Technology Policy, January 1998. Link suggests that public-private partnerships represent a key policy instrument to overcome disincentives to socially beneficial R&D activity.

variety of specific technical, infrastructure, and marketing challenges that many experts believe must be overcome before societal benefits of solid-state lighting can be realized.

Box A: A National Lighting Initiative

The Committee on Optical Science and Engineering of the National Academy of Sciences recommends a national initiative on new lighting sources and distribution systems.[8] It calls for greater coordination, noting that:

"The Department of Energy, the Environmental Protection Agency, the Electric Power Research Institute, and the National Electric Manufacturers Association should coordinate their efforts to create a single program to enhance the efficiency and efficacy of new lighting sources and delivery systems, with the goal of reducing U.S. consumption of electricity for lighting by a factor of two over the next decade, thus saving about $10 billion to $20 billion per year in energy costs."[9]

In the past, government incentives, in the form of awards and procurement, have helped bring new technologies to market. Government-industry partnerships can help overcome these challenges if they are properly structured and effectively led.[10] Previous elements of a multi-year, program-based study by the Committee for Government-Industry Partnerships have suggested that consortia can be an effective means to reduce costs, share information, and help accelerate technological innovation by coordinating pre-competitive research and collaboration on the development of common standards.[11] Collaborative efforts to bring solid-state lighting to the marketplace may help U.S. industry achieve international leadership in this and other new technologies.

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[8]See National Research Council, *Harnessing Light: Optical Science and Engineering for the 21st Century.* Washington, D.C.: National Academy Press, 1998, p. 22, 154.

[9]Ibid. The recommendations of this report were discussed at the workshop by Dr. David Attwood. His remarks are summarized in the Proceedings of this report.

[10]See remarks by William Spencer on the lessons of SEMATECH in the Proceedings of this report. See also Peter Grindley, David C. Mowery, and Brian Silverman, "SEMATECH and Collaborative Research: Lessons in the Design of High-Technology Consortia," *Journal of Policy Analysis and Management* 13(4):, Fall 1994, pp. 723-58.

[11]For a brief review of this federal role in the development of other technologies, see National Research Council, *Advanced Technology Program: Assessing Outcomes,* C. Wessner, ed., Washington, D.C.: National Academy Press, 2001, pp. 11-14.

SUMMARY OF THE WORKSHOP

Many participants at a March 2001 Solid-State Lighting Workshop noted that Solid-State Lighting represents a new generation in lighting technology—one that presents new ways of purchasing, installing, using, and replacing lighting. They observed that Solid-State Lighting has the potential to expand the lighting industry and create new concepts in lighting, and that it promises to be longer lasting, more versatile, safer, more environmentally friendly, and more energy efficient lighting technology than today's incandescent and fluorescent bulbs. According to Charles Becker of General Electric, widespread use of solid-state lighting can bring a 50 to 90 percent reduction in lighting-related energy use in the United States. In turn, this suggests up to $90 billion in gross yearly savings, with related reductions in power plant emissions possible as well.[12]

This report summary brings together the central themes of the presentations and discussions at the workshop. These relate to:

- The current and potential applications of solid-state lighting,
- The current and potential operational advantages of solid-state lighting,
- The potential advantages of widespread uses of this technology,
- Three core challenges facing the solid-state lighting industry in bringing this technology to the market, and
- The potential use of a consortium-based organization to help overcome some of these challenges.

Current and Potential Uses of Solid-State Lighting

Experts in attendance at the workshop cited numerous current and potential applications of Light Emitting Diodes (LED) and Organic Light Emitting Diodes (OLED) as examples. Current applications of LEDs include:

- **Traffic Lights:** The long lifetimes and efficiency of LEDs make them particularly well suited to the job of regulating traffic.[13]
- **Automobile brake lights:** LEDs improve auto safety because they turn

[12]Estimates of reduced energy use and resulting savings are drawn from the workshop presentation of Charles Becker of General Electric. His comments are summarized in the Proceedings of this report.

[13]See remarks by Dr. Chipalkatti and Dr. Craford in the Proceedings of this report. By comparison, traditional stoplights, incandescent bulbs with red filters that block about 80 percent of the glow, reduce the amount of extracted light from about 17 lm/W to about 4 lm/W. Traditional stoplights also have the disadvantage in that the bulb lasts only about a year before having to be replaced, often a challenge at busy intersections. By contrast, LEDs last about 10 years. About 10 percent of the red traffic lights in the United States have now been replaced by LEDs. See Neil Savage, "LEDs: Light of the Future," *Technology Review* 103(5):41, 2000, p. 41.

on in less than a microsecond; tungsten lamps, in comparison, require tens of milliseconds to light up. This means that at highway speeds, a driver following another car will be able to react about one car length sooner to a car with an LED brake light. Small and lightweight, LEDs also help reduce the overall weight of the vehicle, allowing for higher gas mileage.[14]

- **Large Video Screens:** LED video screens have all but replaced cathode ray tubes for large presentations, especially outdoors.[15] The construction of the eight-story NASDAQ wall of light at Times Square in New York City is a harbinger of a new era of display lighting.[16]
- **Retail signs and lighting:** Retailers are experimenting with LED lighting designs.[17] Channel LED systems are beginning to replace neon signs for lettering. They promise a rapid return on investment because of their very low maintenance costs and higher energy savings.[18]

OLEDs—which are a newer, more rapidly developing solid-state lighting technology—have moved in just a decade from scientific curiosity to selected commercial application.[19] OLED devices have the added benefit of being flexible. Their pliability means they can be patterned, printed, and fitted to surfaces of any shape. For example, an organic display on a substrate of thin plastic can be bent around a diameter of less than a centimeter, offering many new possibilities in architecture and industrial design.[20]

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[14]See remarks by Dr. Craford in the Proceedings section of this report. Auto manufacturers are even adopting signature wavelengths so that their LED lighting can be unique. BMWs use 605-nm LEDs in their instrument panels, while Audis use 630-nm LEDs and Volkswagens use yet another wavelength. See Marie Meyer, "'Craford's Law' and the Evolution of the LED Industry." *Compound Semiconductor* 6(2) March 2000, p. 27.

[15]See remarks by Dr. Craford in the Proceedings section of this report.

[16]See remarks by Dr. Kennedy in the Proceedings section of this report. The NASDAQ Marketsite Tower, the world's tallest video screen, uses more than 18 million LEDs covering 10,736 square feet.

[17]See "Shedding Light on an Age-old Retail Question: How to Get Customers in the Door and Keep Them There." <www.colorkinetics.com>.

[18]See remarks by Dr. Craford in the Proceedings section of this report. See also Steve Leinweber, "LEDs in Exterior Applications: An Emerging Market," *E-Source* ER-01017,2001. The "Channel Letter Illumination" of GELcore, a joint venture of General Electric and EMCORE Corp., began distribution in the summer of 2001.

[19]For a discussion of the advantages of OLEDs, see the presentation of Dr. Thompson, in the Proceedings of this report. See also Anil Duggal and Steven Duclos, "Lighting Opportunities for Organic Light Emitting Diode (OLED) Technology," Niskayuna, N.Y.: GE Corporate Research and Development, March 4, 2001.

[20]See remarks by Dr. Kennedy in the Proceedings to this report. The versatility of OLEDs is generating great enthusiasm among some members of the architectural community: "Imagine a light source so integrated with building materials that with the activation of electric current, simple wood, brick and concrete surfaces are transformed into a colorful, kinetic, luminous environment—where the infrastructure of the light source is diminished to virtually nothing while the presence of light is magnified." Christina Trauthwein, "You say you want a revolution....," *Architectural Lighting,* May

Operational Features of Solid-State Lighting

Several workshop participants referred to the operational advantages of solid-state lighting over conventional lighting:[21]

- **Energy efficiency:** Solid-state lighting devices lose little energy in converting electrical energy to light. [22] The internal efficiency of some devices is about double that of a standard 60-watt incandescent bulb.
- **Cool operation:** Solid-state lighting devices today convert approximately 25 to 35 percent of electrical energy to light with the rest dissipated as heat.[23] By comparison, the efficiency rate for incandescent bulbs is only about 5 percent.[24]
- **Long Life:** A typical incandescent bulb lasts about 1,000 hours; a red or yellow LED can last more than 100 times as long.[25]
- **Small size:** LEDs and OLEDs do not require bulky sockets or fixtures. They can be embedded directly into small spaces in appliances, automobiles, or buildings. This allows for more flexibility in designs for lighting spaces, instruments, and buildings.[26]

Potential Externalities of Solid-State Lighting

Broader impacts that widespread use of solid-state lighting technology may bring were also highlighted.

- **Energy savings:** Dr. Ginsberg of the Department of Energy noted that about 18 percent of all electricity in the United States is used for lighting, primarily commercial, residential, and outdoor applications.[27] Wide-

2001, p. 43. For additional discussion of design possibilities inherent in solid-state lighting, see the presentation of Dr. Sheila Kennedy, in the Proceedings of this report.

[21]See, for example, presentations by Drs. Attwood, Chipalkatti, Kennedy, and Thompson in the Proceedings of this report.

[22]This drive for greater efficiency has been spurred by the Federal Ballast Energy Law of 1988 and the National Energy Policy Act of 1992. See Mark Loeffler, "Environmental Initiatives—Toward 'Greener' Lighting." *Architectural Lighting* May 2000, Vol. 15, No. 3, p. 20.

[23]See remarks by Dr. DenBaars in the Proceedings of this report on the performance value of the technology developed by Cree Inc.

[24]Diana Vorsatz, Leslie Shown, Jonathan G. Koomey, Mithra Moezzi, Andrea Denver, and Barbara Atkinson. *Lighting Market Sourcebook*, LBNL-39102, Berkeley, CA: Lawrence Berkeley National Laboratory, December 1997, p. A-3. Vorsatz et al. provide an overview of lighting energy use patterns in the United States and of the marketplace in which lighting products are distributed, promoted, and sold.

[25]See remarks by Dr. Chipalkatti in the Proceedings of this report.

[26]See remarks by Dr. Chipalkatti and Dr. Kennedy in the Proceedings of this report.

[27]A similar figure was reported also in the remarks of Dr. Chipalkatti. Traditional lighting sources include sources incandescent, fluorescent, and high-intensity discharge lamps. Current lighting tech-

spread use of solid-state lighting, he noted, has the potential to reduce consumption of electricity for lighting by 50 percent. This could imply a gross savings of approximately $10 billion per year in the near future, rising by 2020 to some $30 to $70 billion annually.[28] Of course, additional and non-trivial analysis would be required to determine the net economic benefit to the nation of widespread use of solid-state technology.[29]

- **Environmental protection:** Dr. Al Romig of Sandia National Laboratories provided estimates that widespread adoption of solid state lighting by 2025 has the potential to decrease total global consumption of electricity by 10 percent, free over 125 GW of global generating capacity (the approximate equivalent of 125 large power plants), and reduce global carbon dioxide emissions by 200 million tons a year.[30] Relatedly, Dr. DenBaars noted that widespread use of solid-state lighting technology could help bring the United States into compliance with the Kyoto environmental protocol. As noted by Dr. Duclos, widespread use of OLEDs also has the potential to reduce mercury related pollution associated with fluorescent lights.[31] It is important to bear in mind, of course, that there may also be potential environmental concerns arising from the increased

nologies also include some high-intensity discharge light sources, such as mercury vapor, metal halide, and high-pressure sodium lamps. These are most often used in commercial and industrial applications when color rendering is not a high priority. (Vorsatz et al., *op. cit*., p. A-6.)

[28]OIDA, "OLEDs for General Illumination," OIDA Workshop Report, Nov. 30-Dec. 1, 2000, Berkeley, Calif., p. 5. Washington, D.C.: Optoelectronics Industry Development Association.

[29]One assumption implicit in some of the workshop presentations is that solid-state lighting, by replacing less efficient lighting devices, would yield significant gross energy savings. A more complete analysis of the widespread use of solid-state lighting would have to consider the net dynamic impact of this new technology. For instance, under some scenarios, innovative applications of this new technology might create additional demand for lighting, thus increasing energy use. In principle, to arrive at net benefits, one has to account for the externalities that arise with investments in and production of this technology, including opportunity costs of deploying the involved resources in alternate uses. These costs, whether positive or negative, have to be internalized and then subtracted from the gross benefits to arrive at the appropriate net benefit. While clear in principle, any such calculation is susceptible to the quality and availability of data that can be collected. In general, data as collected better reports what can be measured while understating the potential dynamic effects, such as those that might arise with the widespread adoption of solid-state lighting technology.

[30]Widespread use of solid-state lighting is expected to help mitigate the potential environmental damage from 1,200 Kg/year of mercury (estimated) from fluorescent lighting.

[31]In addition to the remarks by Dr. Duclos in the Proceedings to this report, see Duggal and Duclos, *op. cit*., p. 3. Modest amounts of vaporized mercury have long been used in fluorescent bulbs, because electrical current excites mercury vapor into emitting ultraviolet radiation and causes a phosphor tube coating to glow, or fluoresce (see Vorsatz et al., *op. cit.,* p. A-5). However, according to the National Electrical Manufacturers Association, lighting companies have begun to decrease the mercury content of bulbs. Of 158 tons of mercury released in the United States in 1999, only 1.1 tons came from lamps—a 70 percent improvement since 1990. See Mark Loeffler, *op cit.,* p. 20.

manufacture, use, and resulting disposal requirements of solid-state lighting itself.

- **Economic opportunity:** The first companies to bring products to the general illumination market will help set standards, create jobs, and establish market share in the solid-state lighting industry. The global market for lamp products is valued at some $12 billion, including incandescent, fluorescent, and halogen technologies.[32] The display market in solid-state lighting is alone thought to be worth some $50 billion a year in the near future.[33]
- **Enhancement of national security:** Solid-state lighting devices offer major advantages to military systems because they are small, safe, lightweight, reliable, cool, and resistant to heat and ionizing radiation. Dr. Romig of Sandia National Laboratories noted that researchers are already applying solid-state optics in chemical and biological weapons sensing, detection of missile launches, and in a new generation of radar.[34]

Three Challenges in Solid-State Lighting

While some solid-state lighting devices already have successful niche applications, solid-state lighting manufacturers must address the requirements of the market for general lighting if wider adoption of this technology is to occur. Users in this broader market expect LEDs and OLEDs to have similar properties as existing light sources in terms of light distribution, flux density, lifetime, color, ease of use, and other properties. Participants at the workshop discussed the research and development, infrastructure development, and consumer acceptance challenges to bringing solid-state lighting to the marketplace.

The R&D Challenges

Many workshop participants noted that both LED and OLED modes of solid-state lighting must overcome a gamut of technical challenges to reach full commercial application.[35] These technical challenges relate, *inter alia*, to enhancing energy efficiency, improving light extraction and color rendering, reducing manufacturing defects, and extending lamp life.[36]

[32]See M. George Craford, Nick Holonyak, Jr., and Frederick A. Kish, Jr., "In Pursuit of the Ultimate Lamp," *Scientific American,* February 2001, pp. 63-67.

[33]See the remarks of Dr. Duclos in the Proceedings of this report.

[34]See the remarks of Dr. Romig of Sandia National Laboratories in the Proceedings of this report.

[35]See presentations by Drs. Karlicek and van Slyke on critical R&D challenges in the Proceedings of this report.

[36]For an elaboration of these challenges, see the presentation by Dr. Craford on "Barriers to Commercialization" in the Proceedings of this report.

In addressing the technological and cost challenges for both LEDs and OLEDs, engineers need new, accurate standards to measure light and color, as well as non-destructive methods to measure and monitor other properties of semiconductor materials to reduce defects. For example, a definition of "good" white light must be developed based on customer requirements for different applications.[37]

Box B: Three Technical Challenges to White Light

In his presentation, Dr. Karlicek summarized three challenges that faced the industry in its effort to develop white LEDs:

1. The first is performance, or lumens per watt (lm/W). Traditional lighting sources emit 10 to 100 lm/W; LEDs in the research lab have been reaching about 25 lm/W. A single traditional white-light bulb emitted a kilolumen or more. This, he said, presents a "rather large performance challenge."
2. Costs need to come down. Traditional bulbs cost about a dollar per kilolumen, LEDs around $500 per kilolumen.
3. Packaging, he said, will be a "gating factor," not only in terms of efficiency but also as an interface between application and fixture. A lot of work has not been done on packaging.

Dr. Gebbie of NIST pointed to need for common standards in coordinating research on white solid-state lighting. Human subjectivity, she noted, poses particular challenges in measurement and standardization; NIST is developing innovative strategies to overcome this problem.[38] She noted that NIST could help

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[37]See remarks by Dr. Brown of NIST in the Proceedings of this report. See also OIDA, *op. cit*., p. 37. A major challenge in expanding broad based consumer acceptance of solid-state lighting is the technical mission of producing sources of white light that are bright, natural in appearance, and economical. The first way is to combine the output of red, green, and blue emitters, just as a television set makes use of glowing red, green, and blue pixels. The second way, chosen by Nichia, uses LED photons to excite a phosphorescent coating that then emits white light. A third method of producing white light combines elements of the first two techniques in a process of photon recycling. See Savage, *op cit.,* p. 43. White LED light can also be developed using an ultraviolet approach. Here, an LED that emits in ultraviolet is coated with a phosphor powder that absorbs the UV non-visible light and converts it into white light. This work is taking place under a NIST Advanced Technology Program award where Cree Lighting and GE Lighting/GELcore have a joint project for UV development work.
See ≤www.acq.osd.mil/bmdo/bmdolink/html≥. See also www.cree.com/about/news109.htm

[38]The mission of NIST's photoelectronics division is to provide the industry with "technically advanced measurement capabilities, standards, and tractability to these standards. See www.boulder.nist.gov/div815

reduce such problems by working with manufacturers to address their measurement needs and to coordinate standards internationally.

Developing a New Lighting Infrastructure

Some workshop participants noted that a prospective partnership in solid-state lighting faces the mission of developing and advocating standards for a new lighting infrastructure. Addressing this point, Dr. Chipalkatti noted that Edison's main contribution to a new and revolutionizing generation of electrical illumination rested less in inventing the incandescent bulb than in his vision of an infrastructure to support its widespread use. This involved developing new manufacturing techniques, common bulb sockets, and electrical distribution techniques. If solid-state lighting is to achieve its potential, with corresponding social benefits, a similar vision of the lighting goals and directions for a system underpinning this new technology is required. Indeed, as Dr. Chipalkatti concluded, there is still need to develop the "glue" that holds the elements of the LED distribution system together.

Industry roadmaps, which can be developed through public-private partnerships, can play an important role in this respect. As Dr. Becker indicated in the Proceedings, individual firms such as GE already possess their own technology roadmaps for specialty applications in solid-state lighting, "but what is less clear is how to make the leap to the system level: How can the industry move from small lamps and demonstrations to practical systems that are part of the real world?" To penetrate the general lighting market and to realize potential energy savings, noted Dr. Becker, it is necessary to drive the entire system and to promote the acceptance of solid-state lighting not only by the lighting industry, but also by architects, builders, and ordinary consumers.

Overcoming Psychological Barriers to Market Acceptance

Gaining marketplace acceptance for a new technology can be challenging. Perceived high costs and consumer preconceptions about what a lighting device is supposed to be can pose barriers to consumer acceptance. As Dr. Chipalkatti noted in his workshop presentation, the perceived inhibitive expense of LEDs is "almost a psychological factor." Although the energy savings over the long lifetimes of LEDs are expected to far outweigh their higher initial costs, recent studies of consumer acceptance of compact fluorescent lighting, thought to be more broadly indicative, shows that consumers, in comparison shopping based on the retail cost of a lighting device, are likely to choose the cheaper light bulb, even if it is the overall less efficient option.[39] Such a mindset, noted, Dr. Chipalkatti, has

[39]Following considerable research on consumer attitudes toward compact fluorescent lighting, Campbell found that the most significant barrier to adoption was the high initial cost. Campbell also

inhibited the adoption of compact fluorescent lighting even though they, like LEDs, are far more economical than traditional bulbs over the lifetime of the lamp. This tendency is likely to pose a barrier to the entry of solid-state lighting to the market for general illumination.

In addition to perceptions of cost, another psychological barrier to market acceptance may rest with how consumers conceive of artificial lighting and lighting fixtures.[40] Most of us think of lighting in terms of light bulbs placed within mounted fixtures. Such fixtures, however, often reduce the effective light output of the bulb, often significantly. In addition, lighting fixtures can take up considerable room. To illustrate this point, Dr. Chipalkatti noted, that ceiling fixtures for fluorescent systems require 8 to 12 inches of overhead space. Illuminated LED embedded ceiling tiles, by comparison, would require no extra space. This means that tall buildings using solid-state lighting technologies would have room for an extra floor for every ten to twelve floors. Part of overcoming the barriers to market thus rests with educating consumers about the thinness, versatility, and overall savings potential of solid-state lighting.

In this regard, Dr. Kennedy of Harvard University described two demonstration projects—one in Boston and the other in New York City—designed to build public awareness of the potentials of solid-state lighting. She advocated the use of such public projects as one element to encourage further consumer education.

Meeting Challenges through a Lighting Consortium

The technological and economic hurdles slowing the progress of solid-state lighting technology, coupled with its environmental and energy-saving appeal, have persuaded many leading figures in the field that the potential benefits and structure of an industry-led partnership between the lighting industry and the federal government should be considered. This was one of the key points of workshop presentations and discussions.

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observed that consumers found that compact fluorescent lighting devices were often incompatible with many standard fittings, were not dimmable, were thought to be unattractive, and users were unclear about where to use them or why. See C.J. Campbell, *Perceptions of Compact Fluorescent Lamps in the Residential Market: Update 1994,* Palo Alto, CA: Electric Power Research Institute, 1994.

[40]Barbara Atkinson and others have pointed out that incandescent lamps enjoy the advantages of familiarity, including warm color and ease of use with inexpensive fixtures. See Barbara Atkinson, Andrea Denver, James E. McMahon, Leslie Shown, and Robert Clear, "Energy-Efficient Lighting Technologies and Their Applications in the Commercial and Residential Sectors" in Frank Kreith and Ronald E. West, eds., *CRC Handbook of Energy Efficiency,* Boca Raton, FL: CRC Press, 1997, pp. 399-427.

Advantages of a Consortium

Dr. Haitz of Agilent Technologies noted that while the solid-state lighting industry is approaching its fourth generation of systems, the technical complexities of moving from one generation to the next are significant. He further noted that costs are high, rising each time by a factor of three. He cited the need for a common effort to develop breakthroughs in order for solid-state lighting technologies to become competitive and have an impact on national energy savings. Citing those factors as well, Dr. Chipalkatti of OSRAM-Sylvania underscored the resulting need for a more formal mechanism for cooperation among industries, government, academia, and lighting industry organizations to further technical advance.

Harnessing Complementary Strengths

Several participants stated that a solid-state lighting partnership among academia, industry, and government would have the advantage of drawing on the relative strengths of each. Robert Karlicek of GELcore noted that the overall R&D effort to produce white LED light requires breakthroughs in chip design and manufacturing, improved packaging design, and improved phosphors. These advances will require large contributions from government laboratories in collaboration with industry before commercial development by industry. In other cases, e.g., phosphors, which affect chip performance, the major effort must come from industry, with smaller contributions from academia and probably minor input from government laboratories.

Several speakers suggested that a major advantage of a government-supported collaboration is its ability to marshal diverse expertise from different locations. Steven van Skyle of Eastman Kodak noted that particular national laboratories have expertise in lighting design and lighting engineering, while industry and academia are conducting much of the work on materials and device research. Achieving low-cost manufacturing technologies will require collaboration among these three players.

Improving International Competitiveness

One stimulus for a government-industry partnership in Solid-State Lighting is the perception that U.S. industry risks falling behind its global competitors as an important new industry gathers momentum. The United States faces strong competition from Europe and Asia. Japan already markets the lion's share of LED devices worldwide.[41] Nonetheless, Japan initiated its own government-in-

[41]Japanese companies, which market some eight billion unicolor LEDs per year, have applied for approximately 10 times as many solid-state lighting patents as either U.S. or German companies. See elaboration on this point by Arpad Bergh in his presentation in this report.

dustry consortium in 1998, led by the Ministry of Economics, Trade, and Industry, to develop efficient LED for general lighting. Similarly, Taiwan's government has also made a large commitment to LED technologies.

At present nearly all major participating firms in the global solid-state lighting market benefit from partnerships with their national governments. American firms are the notable exception. Unless U.S. actors move promptly to collaborate more strategically in this field, other nations may take an early lead in commercializing new solid-state lighting products and dominating an important young industry that originally took shape in the United States. In his presentation, Mark Ginsburg of the Department of Energy noted that a U.S. solid-state lighting initiative, similar to those already launched by other countries, is needed to coordinate the funding for the long-term research necessary to bring the U.S. industry forward.

Drawing on the Japanese experience, Dr. Arpad Bergh of the Optoelectronics Industry Development Association noted that Japanese government-industry cooperation in electronics has been very successful. Aided in part by this support, the Japanese industry has already captured about 70 percent of the market share in solid-state lighting. Dr. Bergh stressed that a key role of government in such a partnership is to set strategic directions and to promote networking. Without such cooperative efforts, he warned, individual U.S. firms will have to move toward niche applications. For the U.S. LED industry to grow, cooperation is likely to prove essential. In particular, the development of common standards and platform technologies will be required to reduce costs, encourage widespread commercial use, and thereby capture the societal benefits of the technology.[42]

Realizing Better Energy Efficiency

Another stimulus for a lighting consortium comes from considerations of energy efficiency. Dr. Mark Ginsburg of the Department of Energy observed that, as part of its objective to promote efficient uses of energy, his department has taken a leading role in working with manufacturers to create a comprehensive, industry-driven solid-state lighting initiative. In the Department of Energy's view, the purpose of such a consortium would be to:

- Educate the public and Congress about the potential of this technology;
- Reduce the electric lighting load of the United States;
- Capture the associated environmental benefits;
- Develop an important new industry sector; and thereby
- Exploit previous U.S. R&D investments to capture this industry's high potential for technological leadership, employment, and export revenues.

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[42]See remarks by Dr. Brown and Dr. Gebbie on the importance of standards in developing solid-state lighting technology, in the Proceedings of this report.

Dr. Ginsburg pointed out that a Department of Energy advocacy program conducted a series of overlapping activities in 2000, including the commissioning of five-year technical roadmaps for both LEDs and OLEDs and an energy savings analysis conducted by Arthur D. Little, Inc.[43]

Progressing from Laboratory to Market

While current LED and OLED technologies have been proven at the basic-research level, history shows that some 95 percent of the research dollars are spent in moving new technologies from the lab to the commercial marketplace. As M. George Craford and coauthors have written in *Scientific American*, "[L]arge-scale replacement of lamps for general-purpose illumination are not expected for a decade or two because of the difficulty in making white LEDs efficient and cost-competitive."[44] Roland Haitz estimates that the U.S. lighting industry, left on its own, will advance LEDs only enough to control about one-tenth of the lighting market by 2025. With government help, however, he estimates that the devices could well account for half the market.[45]

In short, despite its promise, continued progress with this technology is not inevitable. Some technical challenges may prove insurmountable at acceptable cost. Most experts in the field appear to believe, however, that meaningful progress in solid-state technology is a question of time, resources, and market acceptance—the latter two being particularly important. While experience with other consortia (such as SEMATECH, and its roadmap) suggests that the rate of technological progress in solid-state lighting can be accelerated through public-private partnership, the rate of such improvement cannot be known *a priori*. Participants at the workshop made no forecast as to the likely pace of this improvement. To address these issues, better information is also required. Developing a roadmap with the requisite information to move elements of the technology forward from the laboratory to the market would be a major contribution. At present, reliable data on energy use for illumination and market data on lighting products is difficult to obtain at the national level. As Vorsatz and others have argued, policies that more effectively support solid-state lighting could be developed if comprehensive data on U.S. lighting energy use were more regularly gathered and analyzed.[46]

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[43]See Steve Johnson, "The Solid-State Lighting Initiative: An Industry/DOE Collaborative Effort," *Architectural Lighting*, Nov./Dec. 2000, pp. 1-5.

[44]See Craford et al., *op. cit.,* p. 67.

[45]See Savage, *op. cit*., p. 44.

[46]See Vorsatz et al., *op. cit*., p. 101.

Learning Best Practices from SEMATECH

Given the worldwide emulation of SEMATECH, many speakers at the workshop referred to the SEMATECH experience.[47] In his workshop presentation Bill Spencer, Chairman Emeritus of SEMATECH, listed some of the main lessons for a successful consortium based on SEMATECH's experience.[48]

- Ensure quality leadership, including key leaders of the major participating industries.
- Convey your message publicly to leaders in the government and private sector.
- Focus the program on key sectors and build on this developed strength, rather than approach the entire industry.
- Set measurable objectives for advancing generic or pre-competitive knowledge.
- Set uniform requirements of participation so that support is not fragmented.
- Plan first, spend later: Roadmaps are needed before consortia can be properly launched.[49]

More recently, important collaborative work among national laboratories and universities has emerged in the printing of computer chips using extreme ultraviolet lithography.[50] The lesson of this and other public-private collaborations is that any future consortium for solid-state lighting must be an industry-driven process. The great range of R&D needs (from basic science to manufacturing infrastructure to whole new industries) are arguably best understood by the industry in close cooperation with universities and government research laboratories.

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[47]To be sure, some specifics relating to the circumstances faced by firms in the semiconductor industry at the time of SEMATECH's birth differ from the realities faced by firms in the optoelectronics industry. As noted in the Proceedings of this report, for example, firms in the semiconductor industry had the advantage of a much clearer research path than that being confronted by actors in the solid-state lighting industry today. There are, however, broader lessons to take from SEMATECH's experience.

[48]For discussion of current national and regional consortia in the semiconductor industry, see National Research Council, *Regional and National Programs to Support the Semiconductor Industry,* C. Wessner, ed., Washington D.C.: National Academy Press, forthcoming.

[49]A key task for the leadership of any prospective partnership in solid-state lighting would be to develop and prioritize action items. The specific goals related to this task are normally best developed in the context of an industry technology roadmap.

[50]This initiative, initially formed by three national laboratories and six private firms, was joined in March 2001 by a seventh firm, IBM.

THE SOLID-STATE LIGHTING WORKSHOP

As recommended by the previous Academy report by the Committee on Optical Science and Engineering, enhancing the efficiency and efficacy of new lighting sources and delivery systems to realize broad-based societal benefits will require a cooperative, cost-shared approach to public-private R&D support. This report of a workshop builds on this previous analysis and highlights a variety of specific technical, infrastructure, and marketing challenges that many experts believe must be overcome before the economic and social benefits of solid-state lighting can be realized.

II

PROCEEDINGS

Welcome

Charles W. Wessner
National Research Council

Dr. Wessner welcomed symposium participants to the National Academies. He described the Academies as an organization that is led and driven by its distinguished members. He thanked panel members for their participation.

He said that the focus of the day was on the "potentially game-changing technology" of light-emitting diodes (LEDs). One objective of the symposium was to define the advantages of this technology for the lighting industry and for the nation and to clarify the challenges faced by the industry in bringing that technology to the lighting market. He then introduced Dr. Bill Spencer, chair of the symposium.

Introduction

Bill Spencer
International SEMATECH

Dr. Spencer described the symposium as part of a program, begun more than two years previously, to study government-industry partnerships. The program had already studied several government-industry efforts, including the Small Business Innovation Research (SBIR) program, the Advanced Technology Program of the Department of Commerce, the NASA Ames Research Center in California, and government-industry partnerships in the United States, Japan, Europe, and Taiwan.

The government-industry partnerships program had moved toward a study of solid-state technologies—principally semiconductors—in an effort to understand the role that technology has played in the New Economy. Specifically, the partnership program has attempted to clarify the role of semiconductors, communications, computers, and software in the rapid GDP growth that occurred between 1995 and 2000. In this sense it focuses on the semiconductor area but aims to examine the broader phenomenon of partnerships that include government, industry, and academia and to illuminate not only the technology involved but also the economic consequences for the nation.

The purpose of the current symposium, he explained, was to hear both from experts on the technology of solid-state lighting and from representatives from both the private and public sector. These individuals would be able to describe the technology in terms of its value to the lighting industry and to the national economy.

A New Illumination Paradigm I

Makarand Chipalkatti
OSRAM Sylvania

Dr. Chipalkatti said that a "shared sense of anticipation" now existed in the field of solid-state lighting and that the symposium was well timed to update the lighting community on current events. At the same time one must have a solid grasp of how to move this interesting phenomenon in science and technology forward into economic reality. One must also know what differentiates the good ideas that languish in the lab from those that become useful features of everyday life.

A truly innovative technology is a "disruptive" influence in that it displaces older technology because of its inherent advantages. The challenge is to understand situations when this has happened before and to understand how to facilitate a similar transition in the field of solid-state lighting.

THE CONTEXT OF ARCHITECTURE

He cited his own ongoing discussions with co-speaker Dr. Sheila Kennedy of Harvard University and the architectural firm of Kennedy & Violich and its efforts to demonstrate this new technology in the context of architecture. He showed a picture of a new kind of structural material: a tile in which was embedded one of Sylvania's LED "modules," the term used for a pre-lamp or proto-lamp. This is a new lighting product that is both structural and has a long life as a source of illumination. Such a product could change the dynamics of purchasing, installing, and replacing lighting. This product could be embedded in a structural material because the long lifetimes of LEDs make it possible to think in terms of some degree of permanence.

THE TECHNOLOGY S CURVE

In contemplating a new technology it may be helpful to look at the technology S curve, which is a rough adoption curve that results from plotting the development of a certain parameter, such as efficiency, against time. When he looked at S-curve data for the first time, Dr. Chipalkatti was startled to find that the products being described were incandescent lamps and fluorescent lamps. Because he worked for a lighting company, the data immediately caught his attention.

When he began working on the research and development of organic light emitting diodes (OLEDs) and LEDs, it occurred to him to try to demonstrate how fast this technology was actually moving. He decided to try plotting the progress of solid-state lighting, using the parameter of efficiency against time. He found that the new technology was following the same S-curve pattern as earlier lighting technologies. Then he extended this plot by using all of their optimistic forecasts and actual research that Sylvania and other laboratories had accomplished. He included discussions in symposiums like the current one, where attendees shared their laboratory experiences and projections through the next decade. He said that the response from those performing the R&D was generally optimistic and that the time had come to act, to "make this happen."

A DISRUPTIVE TECHNOLOGY

He addressed the question of whether LEDs would be a disruptive technology, and whether their adoption would upset traditional lighting customs. The answer is "yes." At the same time, however, many incandescent products and other traditional lamps are already being challenged by LEDs. Incandescents, in particular, are inefficient in terms of light output, especially for monochromatic applications such as exit signs. "To some extent the incandescent lamp is akin to taking a log of wood and lighting it up. It just heats something so hot that it produces light." A solid-state device, by contrast, converts electrons directly to photons without reliance on heating.

Rather than using the term "disruptive technology," Dr. Chipalkatti said that he prefers to describe solid-state lighting as a new technology that will expand the lighting industry, create new concepts in lighting, and extend the concept of lighting in new directions. He used the structural tile again as an example of a function combined with a material that has never been possible before. He hoped that such a possibility would fire the imaginations of users, consumers, architects, and designers to stimulate growth in new directions. Every day, he said, LED technology is leading to new concepts and inventions.

WHY LEDs?

Why, Dr. Chipalkatti asked, are LEDs so interesting? First, they are very energy-efficient light sources. They are already more efficient than incandescent lamps and, because 20 percent of electricity use in the United States is related to lighting, energy experts have estimated a potential annual savings of $30-$70 billion in energy costs by 2020.

In addition, LEDs as a general rule are very long lasting. Different colors have different lifetimes, but the typical red or yellow LEDs have estimated lifetimes of about 100,000 hours, or more than 10 years. Even when they reach this lifetime they do not burn out as traditional bulbs do; rather, they begin to lose brightness gradually but remain useable to some degree. Another feature that brings long lifetimes is their robustness. They are solid-state devices; there are no filaments to break or electrodes or glass to shatter. This long lifetime allows people to spread the cost of their lighting system over a much longer period than traditionally possible.

Another selling point for LEDs is that they are very reliable devices. Because they can be used in rugged conditions, they are well suited for exterior applications such as traffic lights, where the cost, inconvenience, and even danger of changing a light bulb in the middle of traffic are considerable.

Finally, the quality of the light may be adjusted for the user. It is unlikely that a user would want to change from a blue light to red, although this is possible, however more subtle changes may be desirable, such as changing from a warm white light suitable for winter to a cool white light for summer.

A NEED FOR BRIGHTNESS . . .

He discussed some key indicators of future performance, such as brightness. White LEDs are now capable of 15 to 20 lumens per watt, and are expected to reach the range of 100 lumens per watt or more in the next decade or less. This expectation, he said, was backed by laboratory research by all the companies and government labs in this field. Earlier data indicate that prices and performance of new technologies can improve by perhaps a factor of 20 per decade, and that prices may drop by a factor of 10 per decade. The question that remains is, during the introduction of a new technology, what are the critical "trip wires" that trigger broader use of the technology. In the business this is called the price point. Some people have suggested that about 10 cents per lumen is such a point. For the industry to reach this point as soon as possible a more concerted effort by all major players will be required.

. . . AND A NEW LIGHTING INFRASTRUCTURE

Dr. Chipalkatti returned to the phenomenon of the disruptive technologies and to how they had been accepted in the past. He said that the advent of the incandescent bulb and the change to electrical lighting was a far larger technological jump than is contemplated today. The lighting system at the time was run by the natural gas industry, which piped gas to street lamps that were lit every evening by hand. In considering what propelled the replacement of gas lamps it is important to remember that it was not a simple invention. In fact, Thomas Edison was far from the first inventor of an incandescent bulb. Some 20 groups before Edison had worked on this concept for 40 years.

How then did Edison's lamp outstrip all the competitors who had so many years of experience? Because, said Dr. Chipalkatti, Edison had considered the needs of the entire lighting system. He not only kept improving the incandescent material, which is what most people think of as the lamp; but he also worked on the best ways to make a vacuum and to seal the lamp around this incandescent material. Even more revolutionary was the electrical supply system he invented. Edison visualized a system of generators and wiring that would distribute DC (direct current) power to all the neighborhoods around the generator and drive each electric bulb remotely. Of course, the world came to adopt an AC (alternating current) system instead, but if Edison were here today, he would probably feel vindicated because LEDs use direct current.

Building a system that consists of a power source and a distribution environment is one of the major challenges that the LED lighting industry faces. A distribution system must consider various elements as building blocks of a system. It begins with a source of power, which reaches a circuit board; an LED is placed on top of that, and optical elements may sit on the LED.[1] The end products are modules that have printed circuit boards, lenses, and light guides, all of which give flat-panel effects.

WHAT IS HOLDING LEDs BACK?

Dr. Chipalkatti listed a few of the applications in which LEDs are being used today, such as traffic signals and signage, but asked rhetorically why applications had not developed further toward low-level lighting for buildings, directional signs along highways, safety signs, decorative signage, and in-ground lights, given the potential for substantial energy savings. Factors that hold back the LED development are that people are not familiar with them, they are expensive, and they are not yet simple to use. One of the great appeals of the incandescent bulb, aside from price, is its universality. One can buy a bulb from any manufacturer and screw it into a socket anywhere; this socket, called the Edison socket or the

[1]Secondary optics may help focus the light in the desired direction, which is a significant advantage of LEDs. Most other lighting sources give off light that bounces freely in every direction after emission. LED light can be guided exactly where it is needed, without wastage, thanks to the layer-by-layer structuring of the lamp.

Edison base, has the enormous appeal of convenience, which is not true of LEDs today. The "glue" that holds the elements of an LED distribution system together has yet be developed. This does not mean, he added, that the industry should wait until such a system is available. Dr. Chipalkatti urged that we move ahead continually with the latest technology and understand its strengths and limitations.

PSYCHOLOGICAL FACTORS

Dr. Chipalkatti also addressed the perceived expense of LEDs, which is "almost a psychological factor." The energy savings and long lifetimes of LEDs far outweigh their high initial costs. Commercial and industrial users will understand the economies of long-lived lighting, but a typical consumer might look only at the purchase price and stay with a cheaper, less efficient option. This mindset has slowed the adoption of compact fluorescents, for example, even though they, like LEDs, are far more economical than traditional bulbs over the lifetime of the lamp.

This attitude can only be modified through extensive educational efforts. Another psychological factor is the reputation of fluorescent lights for brightness, which apparently deliver about 100 lumens per dollar. Even though a typical fluorescent lamp has a brightness of about 8,000 candelas per square meter, it requires a fixture for mounting, where much of its light is lost through internal reflection. The effective light output is closer to 2,000 candela per square meter, or about 25 percent of the gross light output. Such basic misunderstandings can hold back the LED industry to a substantial degree. Traditional fluorescent space lighting has another disadvantage that is not apparent. Ceiling fixtures for fluorescent systems require 8 to 12 inches of overhead space. (Some ceilings do contain other utility structures, but these could well be placed in the wall with proper planning.) Illuminated LED ceiling tiles would require no extra space, so that tall buildings using solid-state lighting systems would have room for an extra floor every 10 or 12 floors.

REMOVING BARRIERS

The best way to remove barriers based on misunderstandings or faulty premises, he suggested, is to support an industry-academia-government partnership in solid-state lighting. Such a partnership, in addition to the technical advantages of cooperation, would have the visibility and means to better educate the consumer about accepting and understanding this new technology. Some key objectives would be to educate lighting designers and consumers about the value of the technology, develop standard metrics for the lighting industry, and adopt a common vocabulary for lighting functions and products.

Standards are particularly important, as industry has learned from such wasteful competition as the struggle between Betamax and VHS videotape. One area in which cooperation is needed is the measurement of light output, connectors, power supplies, and colors. Already there is an urgent need for uniform world-wide standards for illumination from traffic signals. In the United States, for example, the use of an incandescent traffic-signal standard makes it inherently difficult for local governments to adopt less expensive LED technology.

A NATIONAL LIGHTING INITIATIVE

The next step, suggested Dr. Chipalkatti, is to build a more formal mechanism for cooperation between industry, government, academia, lighting organizations, and the Optoelectronics Industry Development Association (OIDA), which has been very active in this field. Such a solid-state lighting initiative could complete a realistic roadmap, he concluded, to guide the best ways to implement this new technology and to reinvent the field of modern lighting.

A New Illumination Paradigm II

Sheila Kennedy
Harvard University

Dr. Kennedy, who is both a principal in an architectural firm and a researcher at the Harvard University Graduate School of Design, said that she would talk about the role of design research in the development of solid-state lighting. She began with the point that the efficiency and life span of LEDs will open new markets and unprecedented uses for lighting that will have an impact not only on technology and industry but also on education and culture. It seems clear that the next generation of LED applications will not simply be replacement or substitution products. That is, users will probably not screw LEDs into the traditional Edison base that holds our incandescent bulbs. Solid-state lighting technologies will suggest entirely new sets of materials and ways to deliver and use light that go far beyond what she called the current bulb culture of lighting.

She offered several examples of emerging possibilities:

- A network of LED lights loaded into moveable office or house partitions;
- User-controlled colors and patterns of light;
- Recycled lighting (e.g., ultraviolet light that enters a house as sunlight) is absorbed by a curtain in which LEDs are embedded and is re-emitted as colored or white light during the evening.

LEDs IN FABRICS . . .

Such possibilities may sound fanciful, she said, but collaboration between her group and Dr. Chipalkatti's group at OSRAM Sylvania had produced some innovative prototypes. One is a fabric bearing luminescent pigments (called a "give-back curtain") performing dynamically and changing the color of the fabric over time. Another option is to weave LEDs into rug, curtain, or other soft fabric to create a new medium of light delivery. One might be able to read a book, for example, from the light of a throw-blanket made of this material. The blanket could be bent over to produce more light as it is carried around the house. Thus, design research offers tools to imagine new markets, new product applications, and the implications of this new kind of light for daily life. She suggested that design is not simply an end process but an integral aspect of architecture, one of evaluating and accepting technical parameters and creating new concepts about what lighting can be.

. . . AND OTHER BUILDING MATERIALS

Involved in Dr. Kennedy's design research team are people of different levels and skills, including industry leaders, materials scientists, technical people from major manufacturers, professionals, and graduate students. She and her colleagues began by establishing parameters for the design research process: They would plan for systems based on technology that was not yet available. They began by considering the efficacy of luminescence in nature. As an example, she showed a slide that compares the incandescent light bulb with a firefly. The output of an incandescent bulb is about 5 percent light, and the rest is heat; the firefly accomplishes almost the reverse. The significance of this for building design and architecture is that LEDs provide a very cool light that brings into question the principle of incandescence, where light is nearly equivalent to heat. LEDs also offer a miniaturization of light sources. Noting this, the graduate students, even though they were not lighting experts, were able to make a variety of demonstration samples, embedding LEDs into concrete pavers, EL (engineered lumber) plywood, and oriented strand board (OSB). For OSB, which is heavily used in domestic architecture as a flooring substrate, the students found that by slightly changing the composition of the resin binder it would be possible to produce a recycled wood product that gives off light.

Returning to the contribution of Edison, she agreed with Dr. Chipalkatti that part of his genius was to devise a system for electrical lighting, but another part was actually to develop a vision that included needs and products. These products were to have high significance for education and entertainment as well as business. Similarly, the development of solid state is likely to be more than a technical exercise. Dr. Kennedy described it as an interdisciplinary scientific-creative endeavor.

PROGRAMMABLE BUILDING MATERIALS

Dr. Kennedy suggested that a significant new market for LEDs would include large-scale applications in architecture, especially programmable building materials. These might have the ability to transmit light and information by having performative surfaces that integrate multiple functions. She demonstrated a desktop of EL plywood, which because it is engineered from small bits of wood, can contain strips of electroluminescent lights and electrical connections. Thus the desk surface actually provides light, and small hand-held lights could also be plugged in. The electroluminescent light in the surface absorbs light, "remembers" it, and re-emits it in a different color. This brings the possibility of the intelligent control of light with solid state, as the pixilated points of light familiar from television and computer monitors are actually translated into images and information. Solid-state lighting will potentially be able to perform many functions and behave more like media, transmitting information, changing color, and giving the user a high degree of control over color, intensity, and location.

She also described a floor system called a low-velocity floor that consists of shapes of engineered lumber rolled out like wallpaper beneath a thin, compressed plenum, or mechanical surface. Then a cool, thin cushion of air can be introduced to distribute cool air far more efficiently than typical air conditioning blown downward from a ceiling. Another architectural application is a hybrid ceiling that not only creates a pleasant surface to look at but also absorbs sound and provides light. An LED-equipped tile in one lighting configuration could be changed to any other color or ability of light, which indicates a capability of programming architectural surfaces.

She showed a picture of a prototype desk no more then $^3/_4$-inch in thickness that used fiber-optic materials to move light and information through its surface. The same could be done in floors and walls by using solid-state lighting modules embedded in thin panels of acrylic that take advantage of the acrylic's optical properties. Her group has also experimented with thermochromic materials in which light is activated or changed in color by the body temperature of one's hand.

AN IMPORTANT EDUCATIONAL IMPACT

"If our culture is going to change from a bulb culture to this new paradigm of illumination, we need to begin that change in terms of education." Dr. Kennedy described the "incredible value of the public discussion that takes place in the university tradition of sharing ideas." There is also a benefit in terms of professional partnerships between design research and manufacturers that can be "a very cost-effective method for companies to advance R&D, and opportunities for design professionals to make very significant contributions to technology and culture at the national level." Finally, she referred to the significance of the work products themselves. Design research, she said, often yields the missing or key idea that is necessary to move thinking to another level. The prototypes that are produced have public value as demonstration tools and promote public familiarity with new technology.

Dr. Kennedy called on industry and government leaders to do four things.

1. Promote new forms of collaboration between the government and the private sector.
2. Implement new partnerships between manufacturers and design programs in universities.
3. Sponsor project-specific collaborations between industry and government leaders and design professionals.
4. Implement incentives for the use of solid-state lighting in the design of public projects.

TWO DEMONSTRATION PROJECTS

Dr. Kennedy concluded by describing two public projects that have been designed to use solid-state lighting to build public awareness in creative ways. The first, in the theater district of Boston, uses structural glass manhole covers with solid-state lighting technology embedded in them. The second, in New York City, is a commission for seven commuter ferry terminals along the East River to be equipped with solid-state lighting connected to photovoltaic power sources. She advocated the use of such public demonstration projects as incentives to encourage further collaborations between the public sector and the lighting industry.

Panel I: National Goals and Laboratory Contributions

INTRODUCTION

David Goldston
House Science Committee

Mr. Goldston introduced the members of the first panel and praised the topic of the day as being relevant both to current energy issues and to the ongoing debate about the nature of federal science activity.

ENERGY SAVING OPPORTUNITIES IN SOLID-STATE LIGHTING

Mark Ginsberg
Department of Energy

Dr. Ginsberg called the topic of the symposium as "an exciting one, with the potential to not only advance the nation's technical know-how but also to alleviate pressure on the energy crisis and to create high-tech jobs here at home—a nice combination." He cautioned, however, that the development of this technology would require considerable talent and many partners. "The advancement of solid-state lighting is a task far too big for [our department] to do alone," he said.

Dr. Ginsberg heads the Office of Building Technology, State and Community Programs, known as BTS, at the Department of Energy (DOE). Its mission is to work in cooperation with industry and other governments to develop, promote, and integrate energy technologies and practices to make buildings more efficient and affordable. BTS was created to help manage and serve as a catalyst for positive change in the building sector. As part of this mandate BTS has studied lighting sources and systems over a long period and, through that work and through industry-driven roadmaps, it has helped solid-state lighting emerge as a promising technology and a candidate for accelerated development. Solid-state lighting has already demonstrated its superior energy efficiency and longevity in selected niche applications, and Dr. Ginsberg said that the symposium would help to extend this progress through the exchange of ideas.

The Solid-State Revolution

He offered a brief history of the solid-state revolution. The first chapter produced the transistor radio in the 1940s and 1950s, bringing worldwide access to information and entertainment. A more recent development was the possibility of replacing cathode-ray television sets and bulky computer monitors with highly efficient, high-quality solid-state flat screens. Even better screens are promised by organic light emitting diodes, or OLEDs, for which prototypes are already available. In both substitutions each solid-state replacement has proven to have higher quality, reliability, and energy efficiency than its predecessor.

Solid-State Lighting

Solid-state lighting began with inorganic LEDs that were first known as signal lights, employed for on-off applications in electronic devices and more recently in traffic signals and exit signs. BTS believes that sufficient R&D can overcome technical barriers and move solid-state lighting into the white-light market to compete both with Edison's incandescent bulbs and with fluorescent technologies. Just a few years ago it was assumed that LEDs would never have such wide application because of their high cost and limited color. While that debate went on, a quiet revolution led to color breakthroughs and the NASDAQ sign in Times Square with its 16.8 million LEDs.

A more recent technology was initially developed by Eastman Kodak and its partners: organic LEDs, or OLEDs, which may eventually replace the computer screen and computer monitors we have today. OLEDs are already being used in mobile phones and car radios. If research continues to be successful, these OLED displays will eventually be incorporated into such building elements as ceiling tile and other home and office applications described earlier by Dr. Kennedy. These systems may also employ frequencies and signals that are invisible to the human eye, enabling our computer and communication networks to run without wires in the office of the future.

In addition to general illumination and the specific uses for LEDs and OLEDs already described, solid-state lighting may offer benefits to other subgroups of optoelectronics. One is vertical-cavity surface-emitting lasers, or VCSELs, which have the potential to run the fiber-optic backbone of the Internet and perform medical and scientific research.

Energy Savings

Dr. Ginsberg reviewed the energy-saving potential of solid-state lighting. Total energy consumption in the United States in 1998 was almost 95 quadrillion BTUs, or quads. About a third of this energy, or 35.6 quads, was used to generate the electricity used in all commercial, industrial, and residential applications, including lighting. Across all sectors the national primary energy consumption dedicated to lighting is approximately 6.3 quads, or nearly 18 percent of the total electricity used in buildings. The commercial sector uses 54 percent of this, followed by the residential (26 percent) and industrial (14 percent) sectors. Lighting is also a key contributor to peak electricity demand and increases the internal heat load of buildings. For each of the four sectors BTS has targeted those with biggest electricity consumption—primarily residential incandescent and commercial incandescent and fluorescent lighting—as the key areas where solid state will have to be competitive to achieve significant energy savings.

BTS had also estimated how much of the 6.3 quads of energy used for lighting might be replaced. The study considered three scenarios: (1) the base case; (2) a case in which technology breakthroughs are achieved by limited investment and innovation but the cost of manufacturing remains high; and (3) a case in which investment achieves not only technical breakthroughs but also dramatic price reductions to about 50 cents per kilolumen of light.

Dr. Ginsberg presented a bar chart reflecting this analysis (See Figure 1). The first set of the three bars showed the reduction in quads of energy for use by lighting in 2020, which ranged from 0.15 quads for the base case to 2.6 quads for the price-breakthrough case. The second set of bars showed cumulative energy savings achieved between now and 2020, with the potential under the price-breakthrough scenario to save nearly 14 quads of electricity, the equivalent of $93 billion in the United States.

A Roadmap for Lighting

DOE recently sponsored five meetings to develop an interest in white light from solid-state lighting sources. In accordance with DOE's Vision 2020 roadmap, which was developed with industry, these meetings drew on key stakeholders from industry, academia, and the national labs. The invited experts, some of whom were attending the current symposium, identified the technical barriers that needed to be addressed. At the same time they concluded that there are no

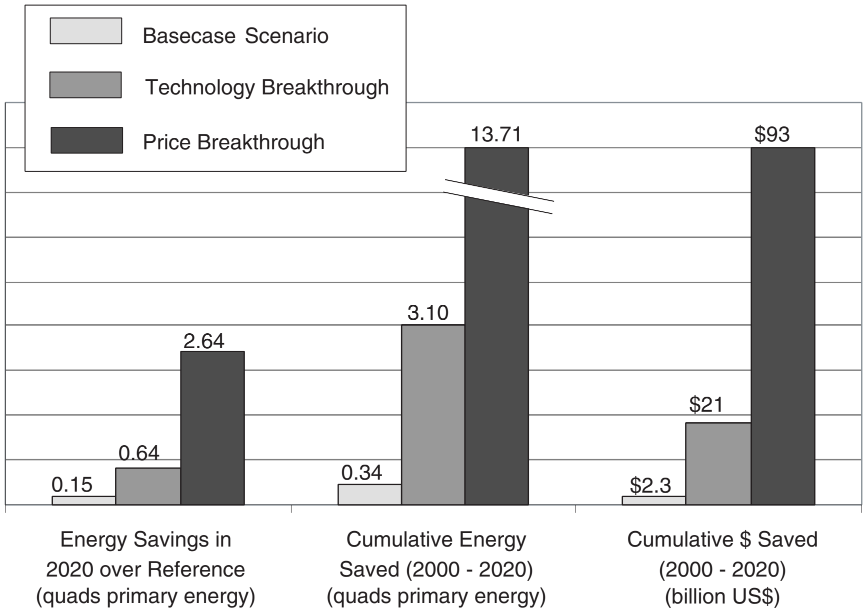

FIGURE 1 Energy Savings Projection.

known barriers to prevent solid-state lighting from becoming the primary source of general illumination lighting. In other words, no new laws of nature or theoretical breakthroughs are required to achieve this goal.

A Time for Acceleration

From this evidence Dr. Ginsberg said that "it's compelling that we should accelerate R&D in solid-state lighting." He summarized the following points in favor of such an acceleration:

- U.S. researchers pioneered the invention of solid-state lighting.
- Solid-state systems are the most efficient way to turn electrons into photons.
- It represents a significant shift in design, products, and lighting systems.
- It creates the opportunity to capture over 2 quads of energy by 2020.
- Solid state is potentially more environmentally benign than current technologies by avoiding the mercury contamination of landfills from fluorescent tubes.
- LED technology development has reached the time when it is possible to focus research on achieving desirable price and performance targets.

An American Solid-State Lighting Initiative

The leap from incandescent bulbs to LEDs, he said, is potentially as great as the leap a century ago from open flame to incandescent bulbs. Completing that leap, however, depends on a national partnership between government, industry, and academia—an American solid-state lighting initiative. Other countries, where national governments play a major role in coordinating and funding the risky, long-term research have already launched such partnerships. Industry by itself is constrained to focus its R&D resources on the immediate markets of signaling and display; it has few resources available for long-term research. That research must be supported by government, he said, and carried out in government labs and universities. With an American solid-state lighting initiative, he said, this country has the opportunity to create a new business sector, reduce national electricity consumption, and allow U.S. technical expertise to commercialize LED lighting technology first.

COMMITTEE ON OPTICAL SCIENCE AND ENGINEERING: STUDY RECOMMENDATIONS

David Attwood
Lawrence Berkeley National Laboratory

Dr. Attwood said he would give a brief report on the work of the Committee on Optical Science and Engineering (COSE).[2] The panel has held numerous hearings and has issued both findings and recommendations on the subjects of optical sensing, lighting, and energy. He summarized recent developments in solid-state lighting sources and said that they "now offer a dramatic new set of options," including LEDs that have the *potential* to be up to 10 times as efficient as standard light bulbs, reducing consumer electricity bills by tens of billions of dollars in the United States. This would bring less pollution, a need to build fewer power plants, and the opportunity to use those monies for other goals.

The COSE Report

In its 1998 report[3] the committee recommended a national initiative that would include such organizations as DOE, the Environmental Protection Agency, the Electric Power Research Institute, and the National Electrical Manufacturers

[2]COSE was formed by the National Research Council in 1995 and is sponsored by the Board on Physics and Astronomy and the National Materials Advisory Board. Its members are drawn from academia, industry, and government.

[3]National Research Council, *Harnessing Light: Optical Science and Engineering for the 21st Century*, Washington, D.C.: National Academy Press, 1998.

Association. The primary objective of the initiative would be to coordinate efforts to enhance the efficiency and efficacy of new lighting sources and delivery systems, with the goal of reducing U.S. consumption of electricity for lighting by a factor of two over the next decade, at a savings of $10 to $20 billion. He also referred to the more recent estimates by Mr. Ginsberg (see above).

He summarized some of the benefits of LEDs, including high efficiency, energy conservation, and low-temperature operation. He also cited the need for materials and manufacturing research, much of it multidisciplinary, to improve and capitalize on these benefits. Much interdisciplinary research remains to be done in the fields of organic and polymer electrochemistry, including the study of the injection and transport of charged species in the medium.

Features of a Lighting Partnership

To accomplish this work, he said, requires a partnership for an initiative in lighting. The COSE report identified the technical challenges, recommended an organizational structure, and outlined the importance of roadmaps to specify the needed steps. It also described key features of such an initiative:

- The key partners: industrial labs, national labs, and universities;
- Primary support needs: industrial and government funding, and creation of a broad-based infrastructure;
- The means to construct the initiative: contracts among private firms and CRADAs between government and the private sector; and
- Legal issues: intellectual property, ownership, and licensing.

An Analogous Effort in Extreme Ultraviolet

He said that the semiconductor industry is participating in a similar initiative to develop extreme ultraviolet lithography. The industry has needed help in developing new, complex techniques to print computer chips, and formed a partnership with the federal government through a CRADA including six companies and three national laboratories. Thus, an industry-driven initiative was created with the goal of extreme ultraviolet capability during the years 2007 and beyond. The technology has emerged out of university and then national laboratory research, and involves three national labs and six semiconductor companies. Dr. Attwood concluded by saying he would discuss this partnership more fully later in the symposium.

NATIONAL SECURITY IMPLICATIONS

Al Romig
Sandia National Laboratories

Dr. Romig turned from the technical description of solid-state lighting to the national security implications of optoelectronics. This subject extends beyond lighting issues, he said, to the base materials that make this technology possible, and it has many applications that go beyond lighting.

Advantages of Optoelectronics for Defense

He said that Sandia National Laboratories serve as a national security facility, and that about half of Sandia's budget is for nuclear deterrence activity. He noted that Sandia was first drawn to the investigation of optical techniques several decades ago because of the many advantages for weapons systems. There are several reasons for this: Solid-state optoelectronic systems containing fiber optic materials are easier to protect from lightning and static discharge than conventional electronic systems and they allow for simpler and more cost-effective designs. In addition, solid-state electronic and optoelectronic systems have also proven their worth in controlling and monitoring weapons of mass destruction because they are safe, secure, and reliable. They are also used in the Division of Energy and Critical Infrastructures for energy, transportation, and information, as well as in "architectural surety" and smart weapons.

Advantages of Integrated Microsystems

One enabling technology now emerging is integrated microsystems, which are particularly cost effective. Integrated microsystems combine the abilities to sense activity, process and store data, take mechanical action, and communicate, either optically or through RF technologies. They allow systems that used to require large spaces or boxes to be miniaturized so effectively that they fit on a single chip. A number of applications using materials that are useful for lighting are also playing a major role in microsystems.

The next leap in microsystem function, he said, will involve more than just packing additional transistors on a chip. It will involve building new microscopic structures alongside the transistors and giving chips the ability to "think, sense, act, and communicate."

Energy as a National Security Issue

Solid-state lighting will contribute to national security by increasing energy efficiency, thus decreasing dependence on foreign energy sources. The potential energy value for solid-state lighting is striking when compared to the inefficiencies of traditional sources. The average efficiency of incandescent bulbs in converting electrical to optical energy is 5 to 6 percent; of fluorescent lights, around 25 percent. Sandia also estimates that solid-state lighting may be able to accomplish the following by the year 2025:

- Decrease by 10 percent the total global consumption of electricity;
- Free over 125 GW of global generating capacity at $50 billion in construction costs; and
- Reduce global carbon emissions by 200 million tons per year.

He emphasized that the availability of energy is a major national security concern, reminding his audience that "we have gone to war over energy in the case of the Gulf War."

Sandia's Solid-State Programs

He reviewed some of the solid-state devices that have been built at Sandia, including LEDs and mini-lasers:

- About four years ago Sandia demonstrated a vertical-cavity surface-emitting laser (VCSEL) that operated at 60-percent efficiency.
- Many military applications of high-frequency light have inspired work not only in the area of phosphides but also a "whole potpourri of things that have driven activities at Sandia now for almost 20 years."
- Nitride materials will eventually play a large role in the lighting initiative and are also important for national security.

The Role of Nitrides

He elaborated on three main areas in which nitrides figure in major technologies:

- **Chemical and biological weapons sensing.** One can use fluorescence-based chem-bio sensors to detect the presence of such weapons. LED-induced fluorescence can be detected from UO_2-doped glass in chemical weapons. Ultraviolet LED-induced fluorescence can also be used to detect biological agents. For example, light in a variety of wavelengths might be used to detect fluorescence from *E. coli* bacteria as well as to detect anthrax spores; a laser of any size can produce such effects, but Sandia has used primarily very small lasers based on solid-state technology, typically a VCSEL. Such a laser can be put into a micro-robot about the size of a quarter.
- **Detection of missile launches.** In sensing weapons of mass destruction it

is helpful that little solar radiation of wavelengths around 250 nm reaches Earth. This is a wavelength where substantial thermal emissions from the plumes of missile launches can be detected. One can build devices based on nitrides that are sensitive to those wavelengths, allowing airborne or ground-based surveillance platforms to search for missile launches. The miniaturization that is possible with solid-state devices makes it possible to fly them on very small platforms. Devices of these wavelengths can also be used for high-frequency radar imaging and high-efficiency, low-weight satellite communications.

- **Synthetic aperture radar.** Sandia invented synthetic aperture radar (SAR), which functions well at night and through clouds. The first SARs, built in the 1990s, weighed several hundred pounds and had to be carried aboard Twin Otter aircraft. Miniaturization with solid-state devices has so decreased the size of SARs that they can now be flown on an unmanned vehicle called a Lynx, which is about 12 feet long. In the near future the weight of SARs will be reduced by another order of magnitude, so that SARs will fly on much smaller and cheaper and more elusive unmanned vehicles. Small size also has the benefits of low power, high gain, and low noise.

A Summary of Advantages

Dr. Romig summarized the usefulness of optoelectronics in defensive applications under four headings.

1. In terms of white light he cited the potential energy efficiency of LEDs, recognizing that the usage and availability of energy is itself an issue that can be destabilizing.
2. A benefit of energy efficiency is that it implies fewer CO_2 emissions and less global warming.
3. Ultraviolet-based optoelectronics bring extensive opportunities in several key defensive areas, such as sensing the presence of chemical, radiological, and biological weapons of mass destruction and carrying them on ever smaller airborne detector platforms. An additional capacity is being able to scan for missile launches.
4. High-power, high-temperature, solid-state electronics can be used in applications like synthetic aperture radar for decoying, jamming, and other functions.

He concluded by noting that optoelectronics also fit well with Sandia's long-held objective of developing sensors that are resistant to ionizing radiation. This is necessary to monitor the nation's nuclear stockpile for radiation leakage. The physical properties of optoelectronics also suit them to many non-defense applications in which high-radiation or high-temperature conditions are hazardous to humans.

Thus, his laboratory has found other dual drivers for optoelectronics, where uses may find applications both in defense and in the commercial marketplace.

MANUFACTURING INFRASTRUCTURE AND METROLOGY FOR LIGHTING

Karen Brown
National Institute of Standards and Technology

The Role of NIST

Dr. Brown, acting Director and Deputy Director of the National Institute of Standards and Technology (NIST), emphasized that metrology is a critical part of being able to bring solid-state lighting to its full potential in the real world. She said that the mission of NIST and its 3,200 employees is "to work with industry to develop applied technology measurements and standards," and that the needs and potential value of solid-state lighting fit this mission well. The institute has a $700 million budget; $300 million of this goes to its laboratories, which study such subjects as building and fire research, physics, information technology, chemical science and technology, and materials science. NIST is applying a wide range of skills to solid-state lighting today, and a key enabler of that is metrology services, or "the ability to measure the output of light sources and the ability to develop standards to make this technology a reality."

She described a similar effort by NIST to promote the semiconductor sector by supporting development of the lithography process. NIST can provide such complex services as light-scattering measurement, optical properties, and materials data. Some of these data help describe the index of refraction of materials, laser wavelength standards, laser power and energy, line-width measurement standards, and artifacts that can be used to calibrate functions as part of the manufacturing process. In other words, it helps with a spectrum of technical needs, from fundamental materials properties to manufacturing properties, according to the evolving needs of industry.

Dr. Brown agreed with the conclusion that LED applications have been expanding rapidly, especially during the last 10 years. She noted that the NASDAQ sign is an example of what can happen in the future: "It's not a dim little thing; it lights up Times Square." The first companies that manufacture high-efficiency white LEDs with good color rendering, she said, have a huge opportunity to capture a market that is not only large but also new in many ways.[4]

[4]Some workshop participants pointed out that companies that are the first to manufacture high efficiency white LEDs with good color rendering will capture a huge market opportunity. Accurate color rendering is extremely significant for the widespread acceptance and application of solid-state lighting in the general illumination market.

The Need for Better Metrology

She referred also to the earlier discussion of the economics of solid-state lighting. To bring down costs, she said, improvements are needed in gallium nitride fabrication, new measurements of process metrology, improved electrical contacts, and improved luminous efficacy, or lumens per watt. To reach any of these goals, industry requires improved measurements and improved materials support. NIST is working in the area of photometric standards for LED measurements and chemical and physical data and measurements for new materials.

Industry needs have driven improvements in LED performance measurements. Manufacturers and users of LEDs have found large discrepancies in their measurements, and the particular directionalities and wavelengths of LEDs create a need for a new way of measuring. In response NIST is developing standard LEDs for photometric measurements with the goal of 2-percent accuracy for LEDs at all wavelengths and colors. They are also developing standard LEDs for color measurement.

A Lack of Metrics Could Limit LED Development

Industry also needs a way to characterize emerging LED materials, such as gallium nitride and related alloys, in order to manufacture blue and green LEDs that are more efficacious at prescribed wavelengths. In particular, NIST is developing non-destructive methods to evaluate defects and their influence on the device properties. This is required to improve the structure and purity of the materials. The lack of methods to measure optical, electrical, and structural properties with nanometer-scale resolution is a primary limiting factor in LED development. One class of techniques being developed for this dimensional scale is non-linear optical analysis.

NIST is also exploring the application of Raman spectroscopy and other methods that are non-contacting, non-destructive, and may be used for real-time process control for manufacturing.

Finally, NIST is using electron microscopy and X-ray diffraction to reduce defects produced when gallium nitride LED chips are connected into microelectronic and optoelectronic devices. The laboratory gathers metallurgical data and measures types and concentrations of defects to point the way to the best low-resistance electrical contacts for use with gallium nitride.

Partnerships with Industry

Dr. Brown emphasized the breadth of the studies under way, both in technological scope and in the variety of participants. In conclusion she stated that the goal of this work is to collaborate effectively with industry to meet the metrology needs of both manufacturing and research. The program addresses the range of R&D from basic research and development to production and applications of LEDs, as well as a considerable effort to understand human-factor responses to light and understand how light is perceived.

DISCUSSION

Current Obstacles to LED Development

Moderator David Goldston asked the panel to describe the greatest current obstacles to the development of solid-state lighting. He received the following responses:

- Dr. Ginsberg said that investment is a key, then technical breakthroughs, and finally "the will."
- Dr. Attwood emphasized the two major phases of developing any new technology. The first is to develop the technology itself and then demonstrate it through laboratory testing and through, for example, limited uses for space or the military. The second phase, which requires major investments, is to "mature" the technology, strengthen its reliability, and raise manufacturing yields. "Historically," he said, "95 percent or more of the cost of bringing any technology to the market occurs in the maturation stage."
- Dr. Brown emphasized the importance of improved standards and measurements. Before any technology is adopted, manufacturers have to agree on standard metrics to describe how it is produced and quantified. This does not mean there cannot be unique applications, she said, but broad-based acceptance across a range of applications requires standardization, at least in the beginning.
- Dr. Romig said that more early-stage research was needed to provide leverage. Development of solid-state lighting requires more multidisciplinary research in solid-state electronics and optical tools, optical luminescence, and polymer chemistry research. Funding for these areas has multiple benefits, because they will have applications to optoelectronics beyond lighting.

Barriers to Acceptance and Funding Needs

Dr. Wessner asked about circumstances during the development of Edison's incandescent bulb and about the magnitude of financing that would be required for a partnership for solid-state lighting. Dr. Ginsberg replied that Edison invented the incandescent bulb in 1889 but that it did not enter widespread use until the 1920s. Acceptance required new manufacturing techniques and electrification of the nation. Other issues were standardization and acceptance of the common bulb and socket, the testing of materials, and the construction of an electrical infrastructure. He said that we can expect quicker adoption today partly because LED innovation is moving rapidly, as exemplified by the NASDAQ sign and the proliferating traffic and exit lights.

In response to the question about funding requirements, Dr. Haitz summarized a study he had conducted some 18 months earlier. He estimated that a government-industry partnership would want to spend about a billion dollars over the next 10 years to accelerate solid-state lighting to a significant degree; in other words, each sector would spend about $50 million a year. He said that the industry is approaching the fourth generation of solid-state systems, and that developing each generation had exceeded estimates of cost and complexity by a factor of at least three. The gallium nitride system in particular is "incredibly complicated" and would require considerable hard work. He added that an efficacy of 50 lumens per watt (l/w) is within reach, but that level is inadequate to have a competitive impact on fluorescent lamps. In order to have that impact and to save energy, he said that well over 100 l/w would be needed. "And that's not going to be done in a slow, evolutionary process. You have to try to develop the breakthroughs."

Solid-State Technology Transfer

Dr. Romig was asked how much technology developed for defensive purposes is transferred to the civilian sector. He replied that much of the research done at the base technology level is transferred. An example of this is Sandia's materials studies of compound semiconductors and high-temperature superconductors. The principal drivers of these studies were the optoelectronics and high-frequency RF applications. The fact that these phenomena now have applications in the realm of lighting is partly a result of learning how to create useful devices based on those materials. He also explained that moving a technology into the marketplace benefits the national lab where it was born. "This is the way I think it's supposed to work," he said, "where basic work with defense applications works its way into the marketplace, gets exercised, developed, and matured, and then fed back into our defense systems."

Panel II:
LED Lights: Emerging Opportunities

INTRODUCTION

Charlie Trimble
Trimble Navigation

Dr. Wessner introduced and congratulated Mr. Trimble for his major contribution to the development of the global positioning system and for his service on the steering committee of the task force on Government-Industry Partnerships.

Mr. Trimble said that he felt like Rip van Winkle in moderating this panel. The last time he had studied LEDs was in the late 1970s, when he worked at Hewlett-Packard. At that time, his company was unable to convince the auto industry of the value of using LEDs for brake lights. Today, he said, the efficiency of LEDs has increased by two orders of magnitude and the auto industry is embracing them rapidly.

THE EVOLUTION OF LED LIGHTS

George Craford
LumiLeds Lighting

The Heart of the LED

Dr. Craford began by describing the basics of LED technology. The heart of the system, he said, is the LED chip itself, which is a semiconductor composed of different layers. The material used in each layer determines the color of the light, and growing the layers carefully affects the amount of light extracted. To make red, orange, and amber LEDs, LumiLeds uses aluminum gallium indium phosphide, or phosphide for short. For blue and green, LumiLeds uses a newer style of chip made of gallium indium nitride, which is grown on a sapphire substrate.

Two central issues, he said, are light generation within the chip and light extraction from the chip. If the first stage is done correctly, light can be generated inside the chip with nearly 100-percent efficiency (i.e., every electron generates a photon). Light can also be extracted with an efficiency of 100 percent, in theory. In practice today the highest light extraction efficiency is about 50 percent. There are many practical barriers to higher extraction efficiencies, including internal reflection and absorption at the metallic contacts, within the semiconductor layers, or in the encapsulation/package.

A History of LEDs

General Electric sold the first LEDs in 1962, based on the work of Nick Holonyak Jr., then with General Electric Research laboratories. They were comparatively dim and very expensive, costing several hundred dollars each. Since the late 1960s, when Monsanto and Hewlett-Packard started marketing LEDs in high volume, their light output has increased by about 10 times per decade. The brightest LED today, he said, produces about 100 lumens per watt (lm/W). He demonstrated one of the small, dim, red diodes made 30 years ago and compared it with a much brighter 100 lm/W LED flashlight. “We’ve come a long way in red,” he said.

Immediate Applications

The value of LEDs can be seen easily in some of their red applications, such as brake lights and taillights. The early Edison bulbs emitted about 2 lm/W; modern incandescent lamps emit around 15 lm/W. When a red brake light is created by putting a red filter over an incandescent bulb, most of the light value is lost, and the output drops to 3 to 4 lm/W. With a red LED, virtually all the light output is functional.

As a result, most of the car manufacturers in the world now use LEDs for their high, center-mounted brake lights. In the Cadillac Deville all the tail lights and brake lights are LEDs, which are not only brighter but can also be mounted in smaller spaces in the car. As a result no space is lost to house bulbs and fixtures. They cannot be seen at all in some applications unless they are turned on. LEDs have also begun to replace neon for signage because of their energy efficiency, reliability, and lack of toxic mercury.

The other successful application discussed at the symposium was traffic signals. The early solid-state models held about 700 LEDs. As brightness improved, this number fell to 200; today's signals contain only 10 to 20 high-powered LEDs. Each signal head uses 15 watts and has a lifetime of 120 months; by comparison, incandescent bulbs use 135 watts and last about six months, a 9x energy savings and a 20x maintenance savings.

While the natural advantages of LEDs are easily suited to these early applications, the next stages of application will require major technological advances. Dr. Craford summarized some technological trends in LEDs that are leading to the next generation of applications.

- **Chips are getting larger.** In the early 1990s, the standard phosphide chip was 0.25 mm square, drawing just 0.1 watt and putting out a few lumens of light. Now a bigger chip, 0.5 mm square, emits tens of lumens. In the newer gallium nitride technology the trend is similar, from smaller to larger, from low to high power; GaN chips now emit up to 50 lumens, and in some research devices, over 100 lumens.
- **Chips are being shaped.** LED chips, which have a high index of refraction, suffer from the problem of light trapping, which limits the extraction of light from the chip. Recently, chips with tapered sides or roughened surfaces have become available. These shapes break the symmetry of the chip and allow more light to escape.
- **More white-light LEDs are being made.** White LEDs have generally been 5 mm in diameter and put out about a lumen of light. These LEDs are not made by mixing red, green, and blue (R-G-B) layers, but by starting with a blue chip and adding a yellow phosphor.[1] This is a simple system, but some efficiency is lost by going through the phosphor. The superposition of R-G-B LEDs to produce white light can yield higher performance, but the blue light/phosphor system is simpler and more convenient for low-power uses, such as in glove compartments and stairway night lights. Higher power LEDs emitting around 20 lumens were recently (late 2001) introduced commercially.

The Major Challenge of Cost

High cost is a major challenge for commercialization. The selling price of a 5mm white-light LED is about 50 cents to $1 per lumen; that same dollar can buy four 100-watt tungsten bulbs. Each bulb emits 1,500 lumens. We thus have up to a 6,000-fold difference in lumens per dollar. Considerable work must be done in manufacturing technology and other fields to drive that cost lower. Costs have been dropping about 10× per decade, and light output per package has been rising by 30× per decade. The rate of cost reduction needs to be accelerated to enable

[1]A phosphor is a substance that emits light following exposure to radiation.

LEDs to compete effectively with conventional light sources for high power applications.

Other Barriers to Commercialization

Several other issues continue to stall commercialization:

- **Reliability.** Red and amber LEDs are very reliable, but the long-term reliability of short-wavelength blue and white has not yet been demonstrated. The devices must be stable at high current density drive conditions to enable the transition to cost effective high power applications.
- **Packaging.** The package surrounding LEDs has to let light emerge more efficiently, be stable against blue and UV radiation, and in high temperature, high humidity environments.
- **Energy savings.** The level of reliability, efficiency, and cost of some LEDs make related energy savings more prospective than real. White LEDs will probably always cost more than traditional bulbs, so they must earn back these costs through low energy consumption. In their favor is that incandescent and fluorescent bulb efficiencies are not improving much with time, while LEDs are improving steadily.
- **Power conversion efficiency.** In combination with red, green, and blue, a 45 percent external quantum efficient LED is not far from 50 percent, because a white light of 150 lm/W could be realized if 50 percent was achieved at all three colors. A red LED with external quantum efficiency of 45 percent, depending on peak wavelength and bandwidth, would have an efficacy of less than 100 lm/W. For the other colors, efficiency falls off. For the nitride system, efficiencies are around 25 percent for UV, 20 percent in the blue, and 10 percent or lower in the green range, so that efficiencies have to improve by a factor of 3 to 5. There is no known theoretical barrier to this goal, but no one knows how long it will take.

In summary, said Dr. Craford, LEDs have advantages in monochromatic applications (such as brake lights). Their use is increasing in those applications, and eventually they will become the standard. They will also be increasingly used for low-power applications, especially where reliability is paramount or bulb changing is difficult, as in tunnel lighting. Before LEDs can penetrate the general illumination market, they need major performance improvements, cost reductions, and better reliability. “Fundamentally, all this is possible,” he concluded, “and given enough time, it will happen.”

NITRIDE LIGHT SOURCE: BLUE LEDs

Steven DenBaars
Cree Inc., and University of California at Santa Barbara

Dr. DenBaars identified nitride LEDs as "the light engine for advanced lighting." He is the scientific advisor to the company Cree, Inc., whose main business is to manufacture high-efficiency, gallium nitride, solid-state light emitters.

Completing the LED Spectrum

The opportunity to make white light was not available until the breakthrough in blue LEDs, he said, which emerged from the pioneering work of several professors in Japan. The ability to produce blue completed the color spectrum, after scientists at Hewlett-Packard had introduced both red and yellow LEDs. Gallium nitrate technology, which led to the development of blue LEDs, now makes it possible to create both white light and high brightness green light. The more recent development of ultraviolet emitters adds a new way to produce white and very deep ultraviolet sources. He called the ultraviolet emitters a unique material with many uses in defense (e.g., for ultraviolet chemical and biological agent detectors and for microwave power transistors). He said that the U.S. government is funding some of this work, but that solid-state lighting itself is receiving as little as a few million dollars per year in public money. He noted that in Japan, Taiwan, and Korea—the other countries leading this effort—research receives substantial funding from their governments.

Moving Toward White Light

"How do we get to white lighting?" Dr. DenBaars asked. He said that the most urgent need is to raise the "wall-plug efficiencies" as well as the luminous output. He added that the flashlights shown at the symposium were "the brightest [LED] sources I've ever seen, and if we can scale that up another factor of ten we can get to the white-light bulb." Also needed are substantial improvements in lifetimes and color rendering.

One of the most challenging limitations of solid-state lighting is the cost per lumen, which is very high compared to other sources. However, government support has clearly improved the technology and has lowered the costs of silicon and gallium arsenide technology; a similar federal effort could accomplish the same objectives for solid-state lighting. Other limitations are low color stability, scaling problems, and packaging needs.

A Demand for Greater Efficacy

He showed a plot of efficacy in terms of lumens per watt. He said that some green-light devices had been able to achieve 90 lm/W, and he suggested that "with modest increases we can be in 150 lm/W range." This would move solid-state lighting into many demanding applications, including streetlights, so that attaining 150 lm/W would be "a game-changing opportunity."

Benefits of Solid State

The benefits of shifting toward solid-state lighting are "enormous," he said, "if we can get to 150 lm/W efficiency and replace 55 percent of existing light sources." He noted Dr. Haitz's calculation that full implementation of solid-state lighting would virtually replace 93 nuclear power plants, and he cited other estimates of as many as 133 power plants, which would have a "huge impact on the environment." This level of energy replacement could reduce global energy consumption by 10 percent, reduce carbon dioxide emissions by 200 million tons per year, and save $100 billion in electricity costs and 1,000 terawatts of power. It would also bring the United States into compliance with the Kyoto environmental accord.

The Complexities of Nitride Technology

Thinking about the place of solid-state lighting in the future, he predicted that nitride sources would be used to generate ultraviolet and blue light, but enormous work was still required to understand the gallium nitride (GaN) nanostructures. For example, after seven years of research it was still not known why it was possible to create efficient GaN LEDs with dislocation densities exceeding 10^8, other than it probably "has something to do with the fundamental nature of GaN nanostructures." All other LED materials require very low dislocation materials. Nor is there yet a satisfactory GaN substrate. Current practice is to put the LED on very lattice-mismatched systems using sapphire or silicon carbide. This difficulty is preventing wide implementation of GaN LEDs at very high currents.

In addition, much work is required in the use of phosphor materials to create white light. Investigation in this area is being funded by NIST through an Advanced Technology program with General Electric, Cree, and GELcore, for the purpose of finding alternative ways to generate white light. For the time being, the commercially available nitride process (which uses a blue LED plus a yellow, garnet-based phosphor) gives a white light, but its color rendering is poor. One experimental approach would be to use ultraviolet or short-wavelength blue LEDs with three types of phosphors (pigments, dyes, and polymers) to yield a white light with good color rendering. Dr. DenBaars predicted that both of these technologies, perhaps with one of them using three red-green-blue LED chips to get white light, will all find different applications in niche markets.

A principal issue to address in nitride technology is the same as it is in silicon and gallium arsenide (GaAs) technology. Process technology is immature; all manufacturers are growing their LEDs on 2-inch wafers, which are too small to be economical. Recently the GaAs process migrated to 6-inch wafers, bringing significant cost reductions; silicon carbide is now grown on 12-inch wafers. Government funding supported the wafer programs, and more of the same, he said, is needed for GaN. If the progress with GaAs is a reliable indication, it will take 5 to 10 years to develop a 6-inch wafer for GaN.

The Filament of the Future

Cree has announced a performance achievement of up to 32-percent quantum efficiency with GaN. In actual watts emitted, these devices gave a wall-plug efficiency of 27 percent. He predicted that the ultraviolet and blue chips would eventually be the building blocks for the high-lumen-per-watt LED lamps, or the filament of the future.

Shaping Chips

Reaching higher efficiencies requires novel chip concepts. Cree has developed ultra-bright chips using a new light-extraction technique. In contrast to conventional square chips, where light "rattles around inside," Cree has been able to enhance efficiency significantly through chip shaping. This design redirects more of the photons out of the chip. The lesson here is that simple changes in manufacturing processes can lead to large benefits in brightness.

The Problem of Overheating

When more powerful LED lamps, such as larger flashlights and room lights, are built, the problem of overheating arises. Engineers have found they can reduce some of the heat by pulsing the light instead of maintaining a constant light. They are now able to reach an efficiency for large chips of about 1.2 watts of ultraviolet light for 9 watts of power flowing in; this corresponds to a 15-percent wall-plug efficiency. This is approaching the range of a small incandescent bulb; a 25-watt incandescent bulb, for example, puts out about 1.3 watts of visible light. Nevertheless, thermal management will continue to be a challenge.

Developing New Markets

Dr. DenBaars predicted that additional markets for LEDs will develop quickly as the technology improves. The flashlight market is promising, because LEDs can reduce the relatively high current cost of batteries. The cost point for an LED flashlight might be around one dollar. The major target market of halogen and incandescent bulbs, however, can be penetrated only after substantial technical breakthroughs. The major challenge is to raise the luminous output by at least an order of magnitude. He visualized two possible commercial modes. One is to fashion drop-in or screw-in replacements for bulbs.

The second challenge is to find more ingenious and appropriate ways of surface mounting or embedding the chips at the locus of application, such as in architectural tiles or dome lights. Embedding saves huge amounts of space in such crowded locations as automobile dashboards, as well as reducing heat output and failure rate. Another potentially enormous market is the backlights for computer notebook displays, where LEDs promise great power savings and extended battery life.

Two Major Challenges: Cost and Performance

Dr. DenBaars summarized the primary technical challenges under two headings: cost and performance. He said that nitride LEDs would be the primary light engine for solid-state lighting technology, once its performance is raised from the current 20 lm/W to 150 lm/W, an improvement "I think we can achieve in a five-year time frame." Also needed is a total output flux of about a thousand lumens for room lighting, which will be driven by large-area epitaxy development and large-area substrates.

It is too early to know whether bulk GaN will eventually be developed, he said; if not, the technology will have to be developed on silicon carbide and sapphire substrates. It is not clear which of these two substrates will win out. Although the technology and its merits have been proven, engineers now have to scale it up. He predicted that once the industry's primary performance goal is attained, "everything will be there. Once we get to 150 lm/W, it will pay for itself in a one-year time frame. That's the message I want to bring. But, we need a big breakthrough to get there, and a focused effort."

AVENUES TO WHITE LIGHT

Katharine Gebbie
Physics Laboratory
National Institute of Standards and Technology

Dr. Gebbie began by describing a conference convened by the Department of Energy in 1998 to discuss the future of lighting and develop a roadmap for the next 20 years. "It was not surprising," she reported, "that in considering solid-state lighting, industry focused part of its attention on the need for objectives, definitions, and standards for lighting quality." Indeed, she said, it has often happened during major technological changes that traditional methods for measuring quality are found to be outmoded and must be replaced by new ones. Producers and customers often find large discrepancies in their measurements without understanding why, and this undermines the confidence of participants in the marketplace.

Defining and Measuring Lumens

Dr. Gebbie said that NIST can help reduce such problems by working with manufacturers to address their measurement needs and to coordinate standards internationally. In describing a series of efforts under way, she noted that while the lumen is based on a well defined measurement of the photopic response of the eye, the perception of color and the quality metrics of color temperature and color rendition are based on measurements using broadband emitters. These metrics are being questioned as combinations of narrow band emitters, qua LEDs, are being created to provide white light.

Difficulties in Measuring Light

Standards that are based on human senses present a problem: A human is needed to be part of the measurement process, but one human may make a different judgment from another. Even the same human will make different judgments at different times. One of the greatest achievements of NIST in the first part of this century, she said, was to create a standard model for human vision. This model, worked out by Gibson and Tyndall in 1923 and fortified by data from some 200 people, determines the relationship between luminous intensity and the visual response of the eye. The model defined the response as a weighted average over a number of wavelengths or colors. Weighting is necessary because, for example, green contributes the most lumens, blue and red fewer.

This functionality model represented an enormous advance in the measurement of luminosity. In 1924 the International Commission on Illumination adopted it as the world standard, and in 1933 the International Committee on Weights and Measures, which is responsible for the metric system, followed suit. In 1948 world organizations for the first time accepted a single standard of brightness (based both on the emission of red-hot platinum at its melting point) and on the response of the human eye. Finally, in 1979 the International Conference of Weights and Measures adopted the present system, which is based on the watts emitted by a lamp. This system still uses the original visibility curve of Gibson and Tyndall.

The 1979 system made it possible to design and build an entirely physical, electrical instrument to measure the brightness of light; NIST's Photometry Standards Laboratory has developed such an instrument. However, this model, she said, still has limitations. For one thing, the world of lighting has changed markedly since 1923, when there were no narrow-band light sources, such as phosphors and LEDs. The human eye may respond very differently to narrow-band lighting than it does to broadband light sources. Nor does the model always predict the accurate brightness even when measurements are made correctly.

Taking Human Factors into Account

Two points, she said, should be emphasized. One is that small differences of

10 to 20 percent in lm/W have no significance in the general appearance of light to humans. Second, if we are to have an understanding of the effectiveness of lighting, human factors must be taken into account and vision experts must be included in research. Two different people measuring the same light can give responses that differ by 50 percent, which is much greater than can be explained by physical differences. Even without including human responses the new demands of spectral distribution require new instruments and methods.

NIST is working to resolve these problems. She described plans to host the second CIE International Commission on Illumination (CIE) symposium at NIST (the first was held in Vienna in 1997 before the recent breakthroughs for green and blue LEDs). In addition, the CIE has established technical committees to develop uniform standards; NIST participates in this process, representing the interests of U.S. industries.

"Good" Light Versus Low-CRI Light

Major ongoing issues revolve around understanding and measuring the composition of light. Isaac Newton demonstrated that white light is composed of a continuous rainbow of different colors; this can be demonstrated by the "rainbow" output of a modern diffraction grating. The reverse is not necessarily true, that is, not all white light is made up of a continuum of all colors. For example, a white light on a TV or computer screen is produced by superimposed pixels of R-G-B light. To incorporate and describe these differences industry has developed the Color Rendering Index (CRI). The highest color rendering value is 100, which may be seen in full sunlight. Values over 80 are considered good. The CRI index for fluorescent range from 62, which is acceptable, to 95, which is high. In general, broadband lighting has a higher CRI and looks more natural than narrowband lighting. NIST's photometry lab is helping to explore ways of raising the CRI of LEDs.

The Need for Better Measurement

Dr. Gebbie summarized her talk by reminding participants of the urgent need to develop uniform ways of measuring and describing the performance of LEDs. The marketplace must understand the new forms of light in terms of quality, comparability, and consistency as well as performance. This understanding, she concluded, would have to involve not only better physical measuring tools but also better knowledge about the responses of the human eye to various combinations of wavelengths.

CRITICAL R&D CHALLENGES

Bob Karlicek
GELcore

Dr. Karlicek said he would review the discussion of R&D challenges that had been raised at the symposium. He began by saying that government support would help address these challenges, especially in view of the competing countries in Asia. Some of these countries have large government-funded initiatives to advance solid-state lighting.

Challenges to the Lighting Industry

He summarized three challenges that faced the industry in its effort to develop white LEDs:

1. The first is performance, or lumens per watt (lm/W). Traditional lighting sources emit 10 to 100 lm/W; LEDs in the research lab have been reaching about 25 lm/W. A single traditional white-light bulb emitted a kilolumen or more. This, he said, presents a "rather large performance challenge."
2. Costs need to come down. Traditional bulbs cost about a dollar per kilolumen, LEDs around $500 per kilolumen.
3. Packaging, he said, will be a "gating factor," not only in terms of efficiency but also as an interface between application and fixture. A lot of work has not been done on packaging.

The technical components of white light can be described under three categories: the LED chip, LED packaging, and the phosphor.

Improving Chip Technology

The big LED cost driver today is the LED chip. One major challenge is that the substrates are very small, and many of them are needed to make large quantities of chips. Substrate size must be increased to produce more chips per wafer. This will become even more important when using larger chips to generate more lumens.

The epitaxy process by which the layers of the chip are grown is a very complex chemical process characterized by large and expensive capital equipment, fairly low throughput (a few wafers per day), and low yield.

Better Chip Fabrication

LED chip fabrication, although similar to the process used to grow chips on silicon, is a manual process. It is not amenable to automation because few companies make equipment that can handle 2-inch substrates. The industry needs larger substrates that are lattice matching. Fabrication of GaN substrates is a technical challenge. Most companies are attempting to use heteroepitaxy, with sapphire or silicon carbide substrate, but some people hope to use silicon wafers with an innovative lift-off technology that would allow the substrate to be peeled off the epitaxial film and either reused or discarded. This would produce large areas of useable chips without the substrate.

Problems with Epitaxy

In the epitaxy area reactor design will be critical. The industry needs to be able to grow high-quality materials in huge volumes (square meters instead of square inches) and it needs better understanding of chemical and flow modeling inside the reactor to improve the yield. One 2-inch sapphire wafer can produce about 14,000 small chips, and yet this may represent a yield of only 20 to 30 percent; most of the product is being thrown away. Substrate and epitaxial growth are two areas where major breakthroughs will be required to move cost performance to a commercially viable level.

Improving Performance

Chip performance also must be improved. All photons originate inside the chip, and the challenge is to direct them outside the chip with high efficiency. At present, he said, his lab is using a gallium nitride crystal structure characterized by fairly high defect densities. There are also doping problems that do not allow optimal electrical conductivity in these materials. This is one reason for the yield problems on these wafers. Extensive research is needed on better lattice matching, heteroepitaxy, and defect modeling.

Another issue in chip performance is efficiency. A gallium nitride chip on a sapphire substrate is very efficient at converting electrons to photons at low voltages, but it is not very bright. At high currents the efficiency is very low. Improving chip efficiency depends on defect reduction, novel designs, and large, efficient chips.

Light Extraction

The challenge of light extraction (guiding the photons out of the chip) involves many of the same issues. Better light extraction requires innovative fabrication techniques, such as chip shaping. This possibility has been understood since the first LEDs were made in the 1960s, but more effective shaping is needed. This may also require either a lattice-matching substrate or improved understanding of how to do heteroepitaxy, where the GaN is grown on different kinds of materials to drive down the cost. Also needed is better modeling of defects and doping performance for these materials to understand their basic atomic structure.

To summarize, chip costs will have to be reduced by 10 to 50 times to be competitive in the marketplace. Major advances are needed in substrate technology, in heteroepitaxy on large wafers, in epitaxial yield, and in wafer uniformity. At the same time, chip efficiency must be increased by three to five times through improved structure design, higher efficiency in materials systems regardless of wavelength, and novel fabrication devices and new structures for better light extraction.

Problems of LED Packaging

An area that is frequently overlooked in high-efficiency LEDs is the package. Since the development of the 5-mm LED lamps of the 1960s, packaging has steadily improved in its ability to tolerate heating and to conduct heat out of the package to the environment. In spite of the improvements thermal conductivity must be raised by a factor of two or three beyond what is now possible. Most LEDs use an epoxy system of encapsulation that does not respond well to high temperatures or to blue or ultraviolet light. Most epoxies absorb a certain fraction of that light and degrade very quickly, letting in destructive moisture and air. This degradation is one reason why white and blue LEDs have short lifetimes.

The challenges to improving packaging are minimizing the heat produced per watt, conducting more heat out of the package, and designing packages that are thermally stable. Thermal management issues are critical for the lifetime, lumen output, and fixture design of high-lumen LEDs. Fortunately, some of the research needed on packaging will also support other areas of semiconductors, including power electronics and applications for communications and military systems.

To improve packaging and increase chip lifetimes, the following are needed:

- A higher index of refraction to match the chip index of refraction, so the light can be extracted from the chip and into the environment;
- Greater transparency of encapsulants to ultraviolet light to avoid photodegradation by the light generated by the chip;
- Thermal stability;
- A good match between the chip's coefficient of expansion and that of the package and the materials that hold the chip in place;
- Good adhesion and low moisture permeability; and
- Development of new polymers or copolymer systems as encapsulants.

Improving Phosphors

Another LED performance driver is phosphors. For chip-plus-phosphor technology, light is generated by the semiconductor and then converted by the phosphor to visible light. Thus the phosphor has two goals: (1) to absorb the light efficiently and (2) to generate the light at a different wavelength with high efficiency. This calls for phosphor systems that are excitable in the ultraviolet or blue with high efficiency. The phosphors must also be packaged in materials with good thermal and chemical stability. The light must cover the entire visible spectrum with good efficiency to create the high-CRI illumination systems that will be required for high-quality white light.

When three (R-G-B) chips are used to generate white light, instead of a chip-phosphor combination, an additional complexity arises. For some materials the correlation of chip output and temperature varies according to color. For example, the efficiency of the blue output goes down with increasing temperature while the efficiency of red-yellow rises. Because of such variations in temperature performance, the system will require not only better thermal performance but also some color-correction circuitry to be able to tune the color. While such circuitry adds expense, it also allows the user to control the color as desired.

Sector Strengths: Academia, Industry, Government

In describing the overall R&D effort needed to produce white LED light, Dr. Karlicek offered a breakdown of the contributions of the academic, industrial, and government sectors. For improved chips, for which device design and manufacturing breakthroughs are needed, the breakdown in funding is roughly equivalent for all three sectors. This is because a high amount of industrial funding is required to develop certain technologies that are close to commercialization, and at the same time multiple breakthrough technologies are needed to bring the needed performance. For improved packaging design, which affects both performance and cost, both new optical polymers and breakthroughs in thermal performance are needed. This will require large contributions from government labs and industry and a smaller contribution from academia. For improved phosphors, which affect chip performance, the need is for new high-efficiency phosphors. Here the major effort must come from industry, with a smaller contribution from academia and minor input from government labs.

The Importance of Design

Finally, he compared LED lighting with traditional lighting and emphasized the importance of design. By properly designing a lighting system a relatively low-lumen LED can actually generate more useful light than an incandescent bulb. He showed a wall-wash application that traditionally might be lit by an 11-watt incandescent with 150 source lumens. Illumination that is roughly two to three times more efficient can be achieved by an LED system using only 1 watt of power and 10 source lumens. A second advantage is that the LED is cool while incandescent burns hot.

Box A. Hierarchy of Needs

Dr. Karlicek summarized his talk by ranking the following needs in order of urgency:

- Basic and applied research on crystal growth, materials, device physics, and optics to improve chip performance: *Major breakthroughs needed.*
- Applied research in supporting technology—Epitaxial growth systems, source purity, flow dynamics, wafer fabrication to increase scale and yield: *Major breakthroughs needed.*
- Basic and applied research in advanced packaging, thermal management, and new optical polymer systems: *Breakthroughs needed.*
- Basic and applied research in phosphor systems for new materials with high absorbency and high conversion efficiency: *Improvements needed.*

In all, commercialization of LED lighting depends on these system challenges:

- Increasing the total lumens per lamp;
- Developing uniform sockets;
- Developing application designs for LED requirements, where the LED and the application are designed to fit one another; and
- Adapting LEDs, which basically run on direct current, to a power supply and distribution system designed for alternating current.

"The bottom line," said Dr. Karlicek, "is that we need major breakthroughs in lighting paradigms to be able to use solid-state lighting and achieve the energy saving benefits they offer."

DISCUSSION

Charles Trimble observed that if one looks at successful partnerships between academia, government, and industry in the computer, semiconductor, and Global Positioning System arenas, one finds several common threads. First, the government invested seed capital in precompetitive research. Second, the government provided early markets for the products. He suggested that the panel address the subject of white-light/LED generation and identify the three most important areas of precompetitive research that are needed. The panel offered the following responses.

A Need for Breakthroughs

George Craford of LumiLeds Lighting said that the nitride technology had come up to a certain level fairly rapidly, but progress had slowed over the last few years. He said that this plateauing is a familiar phenomenon in the development of new technologies. From this plateau the industry still has to improve chip efficiency from three to five times, depending on the color. He said that he had not considered where to draw the line in defining precompetitive technologies, but genuine breakthroughs in efficiency "certainly must happen to allow this lighting technology to take off."

Better Physics

Steven DenBaars stressed the need for better understanding of the physics of light emission, including the characteristics of nanostructures, the role of defects, and the high voltages seen in the nitrides related to p-doping. "The basic materials science is not well elucidated," he said.

Better Measurements

Katharine Gebbie emphasized the need for extensive research in measurements, both precompetitive and infrastructural. Better metrics will benefit all of industry, as well as customers, and will be "absolutely essential" for the field of LEDs to complement technological advances.

Better Knowledge of Chemical Systems

Bob Karlicek said he agreed that the physics of defect analysis of semiconductors and gallium nitride would improve understanding in a precompetitive sense. He also urged a focus on some of the fundamental growth and chemistry issues that go into heteroepitaxy, given the poor likelihood of attaining 6-inch gallium nitride substrates "in my lifetime." Defect analysis, he said, will be a challenge because it requires learning how to drive costs by doing heteroepitaxy more effectively. He also said that infrastructure support, although it is not really precompetitive, would be critical. The bottom line is that more needs to be known about the very complex chemical systems that drive the costs of the LEDs. Having better growth technologies and manufacturing technologies for both fabrication of chips and especially for the epitaxial growth process would help us reduce costs to a significant extent. Unlike the silicon industry, which is a very large business that can pay for a great deal of R&D on equipment, the three- to five-compound semiconductor business is not large enough to do that yet, and the chemical and physical challenges to the growth and fabrication processes are much more complex. The funding challenges are exacerbated by a combination of two factors: an increase in complexity of compound semiconductors and the current small size of the market.

Is Government Support Needed?

Pat Windham asked a follow-up question about funding needs. He cited a perception in Washington that the new, high-tech industries involved in such fields as solid-state lighting are already doing enough technology development, thanks to partnerships with the venture capital industry and large companies. According to this view there is little need for government funding beyond some support for basic research at universities. What, he asked, is the rationale for a larger government role?

George Craford responded that part of the reason for government support is a matter of timing. If the industry is allowed to evolve without any outside stimulus or national policy, he said, it would evolve slowly at a time when the governments of other countries are aggressively funding research. Private firms are limited in how much they can invest in research by the realities of quarterly and even monthly statements, and their R&D money is usually applied to the shortest-range research on new products to generate revenue. The primary beneficiary of high efficiency LED lighting will be the consumer who will save on energy costs. The LED companies will also gain revenue but general LED lighting is perceived to be quite far in the future and is high risk. Given enough time, he said, the industry will eventually develop the technologies needed, but if the nation wants to accelerate that development, it will require some government push in basic research and in development.

Dr. DenBaars pointed out that the industry would not have 6-inch gallium arsenide wafers today if it were not for government support. The same is true for 4-inch silicon carbide wafers, whose development received substantial government funding that helped drive costs down. He suggested that if the industry had a government partner, it might reach its goals of efficient, effective, low-cost lighting in 5 to 10 years instead of 30 years.

Mr. Trimble reminded participants of Dr. Kennedy's earlier assertion that innovative applications, such as architecture and office applications, will stimulate the design of different forms of lighting and the evolution from the point source to the panel. At the same time, the availability of these new forms will be important in identifying and opening new markets. These new applications are sufficiently uncertain, however, that startup and even large companies would not be able to sufficiently fund an R&D process. He agreed with Dr. Craford that the industry would eventually move in that direction, driven in part by the economics of energy costs, but the cost of energy would have to rise substantially before it brought a significant incentive to save lighting power.

A Lack of U.S. Strength in Packaging

In response to a question, a participant addressed the challenge of creating larger wafers and appropriate packaging for more powerful LED systems that give off considerable heat. He said that for larger systems, fabrication technologies could be borrowed from silicon or other wafer-processing technologies. He noted that packaging would be a challenge, because thermal management in high-volume, low-cost packaging is not a forte of industry in this country. For opto-electronics, most of the leaders in LED packaging are now found in Southeast Asia and Japan.

Working Toward Higher Efficiency

Roland Haitz gave two suggestions for the most urgent research objectives of precompetitive research. He said that the efficiency in LED-based lamps was likely to be based on a color-mixing system, where a significant problem is to achieve very good color mixing without excessive loss of light. This goal would involve a search through holographic approaches and "whatever else the physics and optical folks can dream up," and is appropriate for precompetitive research. A second area would make use of Vertical Cavity Surface Emitting Lasers (VCSELS). For this new laser structure, Sandia National Laboratories have recently demonstrated efficiencies above 50 percent at an infrared wavelength of 980 nm. If these results could be extended over the visible spectrum, a VCSEL-based solution would be preferable to the LED-based solution because the photons are easier to direct. Light distribution and extraction efficiency would be substantially more efficient. However, no one yet has demonstrated a VCSEL beyond about 620 nm in the red, which poses a large and interesting challenge for basic researchers.

Panel III: Organic Light Emitting Diodes

INTRODUCTION

Patrick Windham
Windham Consulting

Mr. Windham opened by suggesting that organic light emitting diodes (OLEDs) had an "enormous potential to help replace area lighting, and to do so at a low cost." He mentioned the likelihood that large-area OLEDs will some day be made cheaply by roll-to-roll processing, like newsprint. Like other areas of technology, he said, there are technological challenges to overcome before this can happen, and therefore opportunities for universities, national labs, and industries to work together to improve the technology and make it more cost effective.

AN INTRODUCTION TO OLEDs

Mark Thompson
University of Southern California

Dr. Thompson began by showing the audience a box of red, green, and blue OLEDs. (Unlike the inorganic LED demonstrated earlier, the OLEDs were safe to examine closely.)

The Advantages of OLEDs

The Simplicity of OLEDs

He said that OLEDs got their start in display applications, where they are not only safe but have many benefits that also apply to lighting applications. The first benefit is that the device structures themselves are simple. They consist of a transparent conductor on which lies some number of organic layers, usually four. The total thickness of the organic layer is only about 2,000 angstroms, and that layer is capped with a thin metal cathode.

The Advantage of Flexibility

Another benefit is that all the organic layers are amorphous and therefore bendable. This differentiates them from semiconductors, which are formed by the crystal-growing process of epitaxy[2] and are therefore rigid. OLEDs are so flexible that they can be bent around any reasonable radius and grown as a passive matrix display on virtually any medium, such as plastic sheets or rolls. They can be applied easily to ceilings, walls, or other large surfaces or even embedded in fabrics or other soft elements. They can also be located on or in firm surfaces such as glass, metal, or silicon.

Straightforward Processing

Because organic LEDs are amorphous, the methods for preparing them are relatively straightforward, inexpensive, and can be scaled to large areas. All of the deposition tools for large-scale processing are commercially available. Finally, the lights can be readily tuned in terms of color and electronic properties using chemical means.

There are two types of materials used for making OLEDs: small molecules and polymeric thin films. Electronically the two materials are very similar, although there are some differences in preparation techniques. For small molecules, vacuum deposition is used for both organic thin films and the metal electrodes; the organic compounds are deposited from a heated source directly onto the substrate in a vacuum. Another technique is organic vapor phase deposition, which gives good control over film thickness and composition. For polymers, solution processing (spin coating) is the most common technique. Another technique that Dr. Thompson's laboratory has been developing involves not a vacuum but vapor deposition. This type of process is much more convenient than standard deposition, although the quality of the polymer layers is typically low.

The Advantage of Transparency

Another benefit of these devices is that they are virtually transparent to their own radiation, because the organic layers themselves are very thin. If the cathode

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[2]Epitaxy is the growth of the crystals of one mineral on the crystal face of another mineral, so that the crystalline substrates of both minerals have the same structural orientation. Semiconductors are grown from such solid crystalline substances as silicon and germanium.

is thin enough, one can make devices that are 75 percent or more transparent. By replacing the metal electrode with an electron injection layer, devices have been made that are 95-percent transparent. Because the OLEDs themselves are transparent, different-colored OLEDs can be stacked to combine colors; placing green on top of blue on top of red can create an OLED "sandwich" that gives white light when all three of the devices are turned on. In addition, transparency allows OLEDs to be overlaid on windshields or other transparent substrates where the light can be turned on as needed; when it is off, the view is clear.

Transparency is also valuable in terms of function. Dr. Thompson's laboratory has demonstrated approximately 80-percent efficiency for monochromatic lights. In certain applications, such as games, they have achieved external luminosities as high as 60 lumens per watt for monochromatic green. Lamp lifetimes of 10,000-hour lifetimes are becoming common, and ultimate lifetimes of approximately 100,000 hours (~12 years) are anticipated. Some devices are very bright, with demonstrations as high as a million candelas per square meter, compared with 100 candelas per square meter for a cathode ray tube and 800 candelas for a fluorescent panel. Turn-on voltages as low as 3 volts have been demonstrated.

OLEDs are Specialized

No single device has all of those desirable characteristics; it is unlikely that any single device has even two of them. More typically, devices are designed around particular parameters, reflecting decisions about whether long-lifetime, high-efficiency brightness or some other feature is primary. There are different choices of structure and materials and within the device itself one can use various electrodes, transporting layers, and emissive layers. For the application of lighting, efficiency is paramount, and other qualities may have to be sacrificed.

OLED Function

Dr. Thompson offered a simple description of OLED function, displaying a device package with a two-layer structure. When a fixed voltage is applied, electrons pile up on one side of the organic interface, electron holes[3] on the other. The recombination of electrons and electron holes at the interface leads to a formation of excitons, or excited states, consisting of bound electrons and holes. When the exciton energy is transferred from the host material to the dopant, the dopant emits radiation in the decay process to the ground state.[4]

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[3]In physics a hole (or electron hole) is a vacant position in a substance left by the absence of an electron, especially a position in a semiconductor that acts as a carrier of positive electric charge.

[4]A dopant is a substance, such as phosphorus, added in very small amounts to a semiconductor or an OLED to improve the quantum efficiency of the material.

The Complication of Excitons

At the same time, this light-emitting system encounters another problem. Unlike inorganic devices, OLEDs form two different types of excitons. About 75 percent of excitons form in a triplet-excited state (i.e., three bound excitons), which produces phosphorescence, and about 25 percent occur in a singlet-excited state, which produces fluorescence. Phosphorescence (emission from triplets) is a process that is forbidden in OLEDs by physical laws and thus is typically inefficient. Another way to characterize this is to say that singlet-state excitons quickly return to the ground, or non-excited, state when voltage is removed; the triplet excited state is "forbidden" to return to the ground state, continuing to emit light. This long lifetime of organic phosphors is why a glow-in-the-dark Frisbee can keep glowing for many minutes. While long-glowing phosphors are perfect for nighttime games, they are unacceptable in lighting devices. Most OLEDs produce light by fluorescence (singlets only), thus wasting the majority of the excitons.

Physicists began to tackle this problem through a growing understanding of the photophysics of inorganic compounds. They found that by incorporating such heavy metals as iridium, platinum, and gold, they could get very strong "state mixing" that combines the relaxation of the singlet state with the forbidden relaxation of the triplet state. This dopant-induced state mixing produced very high efficiencies for the relaxations, which largely solved the problem of the triplets. The first proof of this solution came in the late 1990s, when investigators using iridium obtained quantum efficiencies up to around 9 percent and very good efficiencies out to the fairly high brightness of 1,000 candelas per square meter. By further optimizing the matrix into which the dopants are placed, the external quantum efficiency has been raised to 15.5 percent, which is achieved by an internal quantum efficiency of 80 percent. Luminous efficiencies are on the order of 40 lumens per watt.

Glass Mesas for Better Outcoupling

Another issue in the development of OLEDs is internal versus external light, which is also an issue for inorganic LEDs. In a typical organic LED only about a fifth of the light can be directed in the forward direction; four-fifths of the light comes out the sides of the substrate. By extensive experiments in patterning or shaping the substrate, Dr. Thompson's group has shown that they can outcouple a significantly higher fraction of light. They have now raised the outcoupling efficiency from about 20 percent to almost 50 percent, which increases the external efficiency from 15 percent to about 30 percent. They have arrived at fairly complicated substrate shapes called glass mesas. These mesas do not have to be on the front side of the substrate; they work equally well on the backside. Careful work here is necessary for lighting applications, which require every possible photon from a device for acceptable outcoupling efficiency. To date, even the best substrate designs have not yielded high enough outcoupling for lighting applications.

A Chemical Exercise

In many ways, designing different OLEDs is more of a chemical than an engineering exercise. Different devices are made by choosing dopants that create green, red, or yellow light, rather than by optimizing physical parts of the system. An early question was whether the different chemistries would all work to make reasonably effective devices. It turns out that they will, although light output does vary by color. For green, applying one milliamp of current per square centimeter gives about 440 candelas of light per square meter, or about 18 lumens per watt. Output for yellow is not quite as good as for green because of the overlapping of photopic response. For the same reason, output for red also drops to 2.2 to 2.5 lumens per watt.

Needed: More Brightness

In addition, said Dr. Thompson, all of the phosphor or dopants have relatively short lifetimes. They are relatively dim, but no intrinsic decay mechanism has been seen during the first 3,000 hours of operation. An iridium-based system gives a reasonable brightness on the order of 300 candelas and an extrapolated lifetime of about 20,000 hours. While such systems are reasonably well suited for displays, they are about an order of magnitude from the output that will be needed for lighting applications, such as large panel lights.

Mixing Colors

The blending of colors in OLEDs turns out to be manageable, with a number of strategies for mixing colors to produce white light. Dyes can be mixed in the emissive layer of the OLED to convert, in specific contexts, other colors to white, without showing significant changes in color. Individually addressable R-G-B components (side-by-side or stacked) will allow users to set their own color balance for soft or hard lighting.

Another approach avoids having to mix colors in a single device. R-G-B pixels can be arranged side-by-side or stacked, similar to the techniques used to make flat-panel displays. A benefit of this technique is that users can change the color balance themselves. For example, if one color ages more than the others over time, they can correct the balance as necessary. For transparent devices, colors can be combined by stacking pixels one on top of the other. A simpler system would stack large sheets of transparent R-G-B to produce white.

The Advantage of Synergy

Dr. Thompson pointed out that his chemistry group in California worked in close collaboration with electrical engineers in New Jersey at a small, aggressive company. "We need to have this kind of synergy in all of this work," he said. "The best way to move forward is to build as many teams like this as we can that can work on several fronts simultaneously in an integrated fashion."

Poor Packaging

He concluded by saying that while the available options for OLED substrates were becoming clear, the same is not true for the packaging of OLEDs. This continues to present a major challenge, just as it does with inorganic LEDs. Engineers still have not found good ways to achieve a hermetic seal for the substrate or a way to package the substrate itself.

OLEDs FOR GENERAL ILLUMINATION

Steve Duclos
General Electric Corporate Research and Development

A Vision for OLEDs

Dr. Duclos began by offering his vision of "where we see OLED technology taking us" in terms of the benefits, key markets, and R&D challenges. He predicted that OLED technology would lead to the use of large-area, white-light, flat-panel emitting devices. These devices might have one, two, or three layers of organic materials between conducting contacts. The organics could emit in the red, green, and blue, which combine to produce white.

Manufacturing Goals

For manufacturing, the goal will be to mount them on a flexible substrate or film that will enable the use of efficient roll-to-roll processing. The organic materials, because they are amorphous or disordered and not crystalline, can be printed or "splatted" onto the substrate using known methods. These advantages suggest a route to efficient solid-state lighting at inherently low cost.

Large-Area Applications and Energy Savings

OLEDs differ in applications from inorganic LEDs. Inorganic LEDs are best suited to high-brightness point sources of light, such as spotlights, traffic lights, light filaments, and projection lamps. OLEDs will have large-area, diffuse applications, such as backlight, signage, and, most important, light panels for general illumination that can replace fluorescent lamps in ceilings.

This is significant for energy consumption because fluorescent lamps are the largest user of electricity in the lighting sector, which is dominated by the commercial and industrial sectors. Based on fluorescent lamp distribution, it is estimated that OLEDs could penetrate 50 to 70 percent of these sectors and that degree of penetration would save more than 1 quad of energy in the United States. With such savings come environmental benefits: 16 million fewer metric tons of carbon dioxide emissions and the elimination of some of the mercury (used in fluorescent lamps) that contaminates landfills. The commercial and industrial sectors understand the economics of lighting and are likely to respond to such potential savings. If OLEDs reach a light output of 120 lumens per watt, there is likely to be a huge market for them.

Some Technical Challenges

Before OLEDs are ready for this market they must satisfy the technical requirements that will bring the desired color, efficiency, brightness, lifetime, and cost.

- **Color.** Correct white color is critical to market acceptance. This includes color temperature, Color Rendering Index, color uniformity, and color maintenance over the lifetime of the device. White light can be generated by multiple methods, and it is still not clear which will be most effective.
- **Efficiency.** Efficiency is measured in two ways: lumens per watt and external efficiency. Incandescent bulbs achieve about 13 to 15 lumens per watt (lm/W) and fluorescent bulbs achieve about 100 lm/W. However, fluorescents must be placed in a fixture where they lose some light to reflection, reducing efficiency to about 70 lm/W. OLEDs require no fixtures. The goal of OLEDs is 120 lm/W, and to achieve this in acceptable white light they must have an external efficiency (optical watts divided by electrical watts) of 40 percent. Today the efficiency range is 1 to 4 percent for blue, green, and red. An order-of-magnitude increase is needed, which is comparable to the improvement of the last ten years.
- **Brightness and lifetime.** These two qualities are linked: a brighter light usually has a shorter lifetime. Commercial and industrial customers demand lifetimes of at least 20,000 hours, during which the light has to retain a constant color. OLEDs today last about 1,000 hours, so an order-of-magnitude increase is needed here, too. This must be done while solving the problem of differential decay.
- **Cost.** Commercial and industrial customers demand a two-year payback on energy-saving devices. To get there, OLEDs must have an efficiency of 120 lm/W and a cost of $6/kilolumen. Given the economies of roll-to-

roll manufacturing, they appear to have the capability of meeting this requirement. Such economics are persuasive for large customers. OLEDs would provide a savings of about $35 over the lifetime of each typical fluorescent fixture, which holds 3 to 4 bulbs. For large retailers, which can use nearly 5 million such fixtures, total annual savings would be roughly $30 to 40 million.

Hard Work Ahead in R&D

Dr. Duclos concluded by listing a series of R&D challenges that will be needed to raise the efficiency of OLEDs to 120 lm/W, including materials, device design, and large-area processing.

- **Material.** More stability is needed in encapsulation materials, along with better understanding of how to limit major side reactions caused by permeation of air and water into these materials. Fundamental understandings of some of the limiting efficiencies of materials are also needed.
- **Design.** Engineers need to know much more about internal and external quantum efficiencies, how to extract light and reduce light trapping, deposition techniques, and surface texturing. They also need better electrode materials, better transparent materials, and higher conductivity materials.
- **Processing.** Although the potential for bulk roll-to-roll processing is apparent, many engineering questions must be answered, especially how to keep air and moisture out of the device.

He suggested that to accelerate the development of OLEDs, improvements in light efficiency and lifetimes must be improved by approximately an order of magnitude and cost must be lowered substantially. Addressing the three primary R&D challenges (materials, design, and processing) would have to be accomplished in parallel. This, he said, would require the collaboration of industry, academia, and the national labs. If an effective collaboration could be devised, he said, OLEDs have a "real potential for being a very low-cost, high-efficiency replacement for fluorescent lamps" while bringing significant energy savings and environmental benefits.

CRITICAL R&D CHALLENGES

Steve Van Slyke
Eastman Kodak Company

Mr. Van Slyke began by describing OLEDs as multilayer structures for which each layer has a particular function. An entire OLED film is only 200 nanometers or so thick, consisting of anode, hole-injection, hole-transport, emissive, electron-transport, and cathode layers. Light is emitted when a current is passed through the layers; the emissive layer can be modified to give red, white, or blue, for example.

Current Applications of OLEDs

Many companies and universities around the world are working with OLED technologies (see Table 1). Kodak holds over 60 OLED patents and has licensed them broadly. The first company to bring the technology to market was Pioneer, of Japan, making passive matrix displays for such applications as after-market car stereos and CD players. Recently the company brought out larger car stereo displays with a wide-viewing angle, higher-power efficiency, and compatibility with existing electronics. Motorola incorporated a Pioneer OLED display in its cell phones. Another company, TDK, is selling an OLED display to Alpine for car stereos. This display is essentially a white emitter with color filters. Kodak has collaborated with Sanyo to produce a passive matrix for cell phones; its emissions can be patterned with various colors that are "pleasing to the eye and easy to see." Recently Kodak demonstrated full-color active matrix displays using a technique similar to that for liquid crystal displays; the substrate was made of thin-film transistors and each pixel had an R-G-B emitter associated with it.

TABLE 1 Companies Involved in OLED Activities

Europe	North America		Asia	
Avecia	Agilent	Lexell	Canon	Samsung
Aventis	Alien	3M	Denso	Sanyo
CDT	Dow	Siemens	Idemsu	Seiko-Epson
Covion	Du Pont	Three-Five	LG	Sony
Opsys	Kodak	Uniax	Mitsubishi	Stanley Electric
IBM	eMagin	UDC	NEC	Sumitomo
Philips	IBM	Xerox	Nippon Seiki	TDK
	Lucent	Pioneer	Toshiba	
			Ritek	

Difficult Challenges

Color Tuning

OLEDs have the potential of covering large areas; in a typical office half the ceiling might be covered with a white-light OLED. Kodak has experimented with changing emission colors by adjusting the composition of a single layer of the OLED. For yellow and blue emitters, for example, the concentration of the two colors can be tuned to change from blue to reddish yellow, with white in the middle. While this device is effective, it is not yet efficient. He said that simultaneously developing all of these key qualities would require the well-planned collaboration of industry, academic, and government-lab researchers.

The Degradation of Light Quality

Another challenge is to halt the degradation of light quality over the operational lifetime of the OLED. The typical white OLED, operating at an initial power of 500 candelas per square meter, suffers a "steady, monotonous, irritating degradation" that eventually causes lighting efficiency to decline by about half. The display industry could tolerate such a degree of degradation, but the lighting industry could accept a degradation of less than 5 percent over a lifetime of about 10,000 hours. It has proven difficult to understand the causes of instability, and considerable R&D is needed to elucidate the mechanisms.

The Drive for 100 Lumens

Improving efficiency may prove to be less problematic, although the improvements needed are indeed large. Fluorescent bulbs produce about 100 lm/W (before losses to the fixture); by comparison, current white OLEDs achieve only 3 to 5 lm/W, indicating the need for a 20- to 30-fold improvement. The "carrot" in this pursuit is that green OLEDs already yield more than 30 lm/W. "My opinion," said Mr. Van Slyke, "is that you're going to get to 100 lumens. It just depends on how much time and money goes into the effort." He added that it is very difficult to extract enough light out of a device. Only about 20 percent of the light generated in an OLED display emits from the front; the rest leaks out the edge of the display. Solving this challenge will require a great deal of device engineering.

Encapsulation Is Inadequate

Another R&D challenge for OLEDs (which mirrors that of inorganic LEDs) is to develop better encapsulation techniques. All the devices now on the market and being tested have an overly complex encapsulation system. With organic layers deposited on a glass substrate, the anode or the cathode layer is a very reactive metal, requiring a stainless steel "can," a glued perimeter seal, and a desiccant inside the seal to capture any invading moisture. This system is too complex and expensive for the competitive lighting industry. The next-generation device is entirely thin-film encapsulation on a plastic substrate. This system places great demands on the film substrate, and new encapsulation methods must be developed to prevent any moisture from entering and reacting with the cathode metal.

Benefits of a Consortium

He concluded by describing some of the benefits of a government-supported collaboration. One is its ability to marshal diverse expertise in different locations. For example, the national labs have broad expertise in lighting design and lighting engineering, with specific expertise at Pacific Northwest National Laboratory in encapsulation methods that use thin-film technology. For materials and device research, much work is being done by industry and academia; manufacturing technology requires collaboration between industry and the national labs to drive the cost of fabrication as low as possible.

DISCUSSION

Current Federal Support

In response to a question about the level of federal effort, Mr. Van Slyke said that DARPA (the Advanced Research Projects Agency of the Defense Department) was spending $10-12 million per year on LED research, and that the Department of Energy supports a program at General Electric on OLEDs for lighting.

The Degradation Process

Another questioner asked about the nature of the degradation mechanism that shortens the lifetime of OLEDs. Mr. Van Slyke said that one cause is the presence of impurities. Researchers have gradually learned that “purity” in the sense used by organic chemists is not enough; OLEDs need the degree of purity used in the electronics industry. Another mechanism may have to do with hole injection, which is a positive charge injection into one of the layers that creates a cation. Finally, the cathode itself degrades. Dr. Duclos said that the material with the shortest lifetime is the blue and speculated that this may be because the light is emitted close to the band edge of the materials.

Dr. Thompson emphasized that addressing degradation is difficult because the matrix of OLEDs is inherently complex. In any device, there are different materials that all have to be optimized for both lifetime and efficiency. “We don’t know enough about the degradation mechanisms to know which things we need to avoid,” he said. “Even worse, we don’t know what combinations of things we have to avoid. One material may function well in one device, but when it is coupled with another (electron transporter, for example), you may get degradation. It’s a complicated issue.”

Another questioner raised the issue of dark spots, which Mr. Van Slyke said are caused when moisture leaks into a device. He reiterated the need for better encapsulation. Referring again to the work of Pacific Northwest National Laboratory, Dr. Thompson said that researchers there had made OLED films with permeability so low they could not measure it, and even those films could not keep moisture out. "The OLED itself," he said, "is actually a much better permeability test than anything they have for measuring permeability."

Private-Sector Investment in LEDs

Dr. Wessner asked how much is being invested in research by the firms represented at the workshop, by the U.S. government, and by other countries. Mr. Van Slyke said that Kodak had no allocation for OLED lighting and that all of its R&D is directed at display applications. This amounts to some 50 to 60 people, with a budget of over $10 million a year, "still a small amount." Dr. Duclos said that General Electric has a three-year contract with the Department of Energy to demonstrate OLED lighting with higher efficiency than incandescent bulbs.

A Manufacturing Strategy

Dr. Duclos commented on work being done abroad, citing intense activity in Asia over the last three years. He said that Japanese firms had applied for some 8,000 patents related to OLEDs with the expectation that OLED displays would capture a significant fraction of the $50 billion display industry in the next 5 to 10 years. He said that one way to maintain leadership in OLEDs is to push the development of roll-to-roll manufacturing and flexible substrates, where the United States is the leader. He called for a government partnership in this area. Dr. Thompson added that the cost of substrates must come down before the industry can make an economic argument for OLED lighting.

Intense Activity in Asia

Dr. Bergh expanded on the subject of competitiveness. He agreed that in the last two years Japanese firms had issued some 9,000 patents in OLEDs. He cautioned that this figure could not be compared one to one with American or European patents, because the Japanese patent system permits only one claim per patent. To compare them, one has to divide the Japanese number by approximately three. Nonetheless, this figure is far higher than the number of patents obtained by European (400) and American (500) firms in the last year.

The Need for an Outside Force

Dr. Bergh also emphasized the importance of the differing requirements of the lighting and display sectors. Research on the two sectors can be combined only if an outside force guides the industry toward broader objectives. Industry will not voluntarily commit itself to lighting research if reliability and efficiency still have to be improved by more than an order of magnitude. Industry can only move toward general lighting if the government steps in, coordinates the forces in the industry, and leads it to that goal. Lighting requires research programs that are longer term than industry can afford.

Dr. Thompson agreed that the industry is doing the best it can, given the technical challenges. He added that display and lighting applications differ in costs. While the display industry wants lower costs, the lighting industry absolutely has to have them.

OLEDs versus Solar Panels

A questioner asked whether the lighting industry use available thin-film solar cell technology, especially for OLEDs. Dr. Thompson agreed that the best OLEDs are based on the same concepts as thin film solar cells, but he noted an important difference. If an OLED loses 5 percent of its efficiency to creeping decay and dark spot formation, it is ruined; if a solar cell loses 5 percent if its efficiency, it simply produces 5 percent less electricity.

The Argument for a Government Role

Mr. Trimble commented that if the United States wanted to create the success for OLEDs that it achieved for the semiconductor and computer industries, the government must play a similar role; that is, the government must generate a market for panels by announcing large procurement goals for lighting panels, say, a million square feet. This, he said, would do more than anything else to focus attention on this valuable technology.

Dr. Duclos agreed on the need for a government-led effort like SEMATECH, as well as more infrastructure research in the national labs and basic research by academic scientists and engineers. He noted that General Electric is working with the help of its Department of Energy grant to produce a 2-foot-square OLED panel on glass with the same efficiency as incandescent light. He expressed gratitude to the Department of Energy for its support. Dr. Chipalkatti and Mr. van Slyke agreed that even the largest private companies cannot afford all the research necessary to bring OLED lighting to market quickly, and that a "lighting SEMATECH" is required.

Panel IV: Solid-State Lighting Roundtable

INTRODUCTION

Clark McFadden, Moderator
Dewey Ballantine

Dr. Wessner introduced Mr. McFadden, who has played a major role in industry-government partnerships, including SEMATECH. Mr. McFadden said that the current STEP initiative, under the leadership of Gordon Moore, had examined partnerships of different areas, sizes, scopes, and effects. He said that a partnership for solid-state lighting "seems promising," with the potential for major savings, new applications, and new technologies. Most of the elements of a collaborative initiative are within reach, he said, and the challenge now is to find the best plan for moving forward. He noted the many years required to move the light bulb from its first demonstration to widespread use and urged a more expeditious pace in bringing OLEDs to market, with greater benefits for all participants.

CAPITALIZING ON INVESTMENTS: THE INDUSTRY POTENTIAL

Steve Domenik
Sevin Rosen Funds

Mr. Domenik characterized himself as both an entrepreneur and a supporter of ventures in technology development. He said he had come to the workshop primarily to deliver a "short message of optimism" and to suggest that the venture capital industry could assist in creating government-industry initiatives. The solid-state lighting industry, he said, had reached a technical stage where it needs outside funding to pool its resources and coordinate R&D efforts. He made the point that in the not-too-distant future, when systems are ready for commercialization, the venture capital industry would likely be interested in helping and participating.

The Rapid Growth of Venture Capital

He sketched a picture of the rapid growth of the venture capital industry over the last five years. While he predicted some retrenchment after the stock market decline of 2001, the industry has the capacity, even in his own small partnership, to take technologies all the way from the lab to the marketplace. In addition, the growth of the industry means that it is more competitive and individual firms have to seek promising technologies and take the great risks.

This has not always been the case. Until about 1995, the venture capital industry invested a few billion dollars a year in new enterprises. The average investment required about seven years from time of investment until it was possible to sell the investment. In the last five years, he said, the size of the industry has mushroomed to a hundred billion dollars or more per year. This growth attracted many new people and firms to the business and many of the businesses they invested in had questionable or no technology content.

The Stock Market Correction Is Not All Bad

The 2001 stock market correction, he suggested, would be beneficial in the longer term, as people begin to correct their thinking about the venture capital industry. With the NASDAQ down by about half, there is half as much money to invest; many venture capital funds have vanished, and more will follow. Those that remain, he said, will regard their investments more soberly. The returns will not be as exciting or as quick, and investors will expect to be paid for results rather than promises. Having a smaller pool of money (perhaps $50 billion a year rather than $100 billion) will not be all bad. This amount is still an ample pool, and it will continue to be fed by those for whom venture capital is part of their allocation model: wealthy individuals, university endowment funds, and pension funds.

A Partnership Between Venture Capital and Industry

A key point, said Mr. Domenik, is that over the last 5 to 10 years there has evolved a partnership between venture capital and industry, especially in the United States. This bond is so strong that industry has now come to rely on venture-capital-funded enterprises for the commercialization of new technology. One reason for this dependence is that when a private firm underwrites a $50 million development project, it must find a way to record the equivalent of a $50 million loss on its financial reports. When a venture capital firm takes a loss, it is a private matter not reported on any public income statement. On the other hand, if the investment succeeds in creating a viable business, a public company can acquire that business and place it on their balance sheet at effectively no cost. Even in the current downturn, he said, his firm is approached by companies that want to bring the products of young firms to the marketplace, either through acquisition or through partnership.

More Competition Between Venture Capital Firms

Another consequence of the growth of the venture capital industry is that it is much more competitive. This business "used to be a bunch of middle-aged technology executives investing in deals with their friends," said Mr. Domenik. "It has become much larger, more institutional, multinational, multiracial, broad based." The competition is driving firms to invest in earlier-stage, higher-risk activities. Some of the projects Mr. Domenik's firm is pursuing involve university professors in their laboratories supported by government grants. "Every one of these are early enough and risky enough," he said, "that it keeps me awake at night."

With the growth of the venture industry, individual firms have specialized. Some invest at very early stages, like Sevin Rosen; others invest at later stages of development. Mr. Domenik's firm, after 20 years, always invests during the early stages, specializing in technology and practicing a hands-on approach.

The Example of Capstone Turbine

An example of the companies Sevin Rosen has invested in is Capstone Turbine. Eight years ago this company was the risky but promising idea of a group of former rocket engineers who wanted to develop a new microturbine technology for distributed power generation and other uses. This technology, which had received early-stage support from several government initiatives, showed great promise but was far from commercial readiness. After more than $200 million of development work, the technology had proven to be reliable, versatile, and popular, and the once risky investment has paid off in a successful IPO and rapid subsequent growth.[1]

Mr. Domenik closed by saying he would like to see a solid-state lighting initiative succeed. It has excellent technical content, he said, as well as huge

[1]Capstone Turbine Corp. went public in June 2000. Its line of MicroTurbines operate on the principle of a jet engine and can use not only natural gas, diesel, kerosene, and propane but also underutilized or waste fuels, such as oilfield gases. MicroTurbines power hybrid-electric vehicles, convert waste gases into electricity, run micro-cogeneration plants, and perform other functions.

demand and social benefit. Even though his firm does not normally invest in pure science projects, he sees an exciting potential for commercializing solid-state lighting.

A PARTNERSHIP OPPORTUNITY?

Arpad Bergh
Optoelectronics Industry Development Association

Dr. Bergh asserted that government involvement in partnerships usually brings a variety of benefits that are not well recognized. In Japan, the government-industry relationship in electronics has been very successful; a decade ago, Japanese industry was fully networked while American industry was not. He suggested that this was at least part of the reason why Japan's market share in optoelectronics was 70 percent and U.S. market share was 10 percent.

Government's Role in Networking and Setting Direction

One important function of government in such a partnership, he said, is to set strategic directions and to promote industrial networks and collaborations. When private firms are not networked, each will move in separate directions toward niche applications. For the industry as a whole to move toward a common goal, such as the use of LEDs and OLEDs for general lighting, there must be some mechanism to coordinate objectives and agree on directions. He referred to several successful instances of this. DARPA and the National Science Foundation had played major roles in providing a vision for the U.S. communications industry, which thrived under government guidance; the U.S. share of the world market in optoelectronics has grown from 10 percent to about 35 percent. Another compelling reason to network industry is to build an intellectual property base. Finally, as the experience with SEMATECH showed, it is necessary to build a manufacturing infrastructure, and this requires collaboration.

The Role of OIDA

In addition to a government partnership, Dr. Bergh explained the need for an industry association such as OIDA. That association now has 70 members; in addition to the voting members and associate members (including the major lighting companies), university centers have joined as affiliate members. Its mission is to promote optoelectronics worldwide and to advance the competitiveness of its members. OIDA has four functions aimed at building up competitiveness: (1) understanding the markets that pull industrial activity; (2) identifying the technologies that are needed to reach the markets; (3) understanding the infrastructure needed to expedite this technology; and (4) providing a unified voice for the optoelectronics industry in communicating with the government and coordinating funding activities. He added that OIDA could not have progressed on solid state lighting without the close collaboration of the Department of Energy.

A Totally New Industry

He emphasized that the mission of OIDA is not to replace the light bulb; rather, it is to replace conventional lighting with a totally new industry and a new way of understanding lighting. He compared this change to the transitions from vacuum tubes to semiconductors and from cathode ray tubes to flat panel displays used in portable computers. In the "new lighting" there will be two kinds of light sources: inorganic LEDs, which will provide replacements for most incandescent lamps and other point sources of light, and OLEDs, which will replace fluorescent bulbs as area sources. To develop the technologies needed for both efforts, OIDA has performed extensive roadmapping with DOE and has identified milestones that must be reached to penetrate these markets. In inorganic LEDs, the organization has received major support from Sandia National Laboratories, which has been exploring LEDs for many years.

Reasons for Optimism

Dr. Bergh saw reason for optimism because of considerable efficiency improvements lately on both fronts. These improvements allow OIDA to project a level of lighting performance that far outstrips conventional light sources. He agreed with Dr. Haitz, a pioneer in LED applications at Agilent, that inorganic LEDs would someday reach 200 lumens per watt (lm/W), "although some people think the final figure will be closer to 150." "People always underestimate new technology," he added, but warned that the higher target would be achievable only with a partnership that included government support as well as government laboratory and university researchers. "Without this, industry will go to niche markets and will not penetrate any of these domains."

Changing Lighting Altogether

A national program, he said, would "change lighting altogether." One major change is that solid-state lighting for the first time separates the source of energy from the radiation itself. For example, an ultraviolet source and a phosphor can be coupled through space, making the light appear at a location different from that of the source. In addition, solid-state lighting would bring many new applications, environmental benefits, and a new lighting industry. These reasons have already prompted other countries to step ahead of the United States with major government-sponsored activity, especially Korea, Japan, Taiwan, and parts of Europe.

For example, the Japanese NEDO project, Light for the 21st Century, includes well-organized industry participants who focus on substrate to packaging issues in cooperation with a number of universities. The project is operational and has a target of 100 lm/W lighting. Taiwan, the latest country to move into the field, has launched a major activity to set up a white LED lighting industry; a technology promotion office with a budget of $50 million has been set up under the prime minister to coordinate activities. He reported seeing at a Taiwanese trade show a small house on the display floor that was lit entirely with LEDs.

Progress Toward a White-Light Market

The LED industry the United States does exist, with monochromatic applications. The most active markets at present include exit signs, stoplights, and brake lights.[2] Another segment includes active matrix OLED displays. This can only progress to a white-light market, said Dr. Bergh, with a coalition of industry, government, and academia, guided by clear planning and funding. He advocated a 10-year plan leading to significant penetration of the general indoor and outdoor illumination markets. Such a program could help the inorganic LED industry move first into low-flux white lighting, then into high-demand illumination, and finally into general indoor and outdoor lighting. A parallel path could be drawn for OLEDs, moving from display, to decorative, to low-flux white light, and eventually into general illumination. Industry will not take this path by itself, he said, because it is not profitable for companies to make large technological jumps. Instead, they move one step at a time, diverging in random directions wherever the opportunities arise.

National Competitive Needs

He recapped some of the suggestions about what the country requires to move into a competitive position vis-à-vis other countries:

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[2]LED lighting is rapidly becoming the standard in exit sign lighting due to its energy efficiency and long life, but its dimmer light can be a concern in some applications. Exit signs are required by law in all commercial and institutional buildings and must operate continuously. Today, over 100 million exit signs are used throughout the United States and consume 22-35 billion kilowatt-hours of electricity annually. The majority of these signs use incandescent lamps for illumination; so significant savings can be achieved by taking advantage of a more energy-efficient lighting technology. According to the Pacific Northwest National Laboratory, incandescent exit signs cost $42 per year to operate versus $5 per year for LED exit signs.

According to the Department of Energy, LED traffic signal lights use 85 percent less electricity than incandescent bulbs and last about 12 times longer. With about 11 million signals controlling 275,000 U.S. intersections, replacing incandescent signals with LEDs would reduce energy usage by 2.7 billion kWh per year and save U.S. taxpayers an estimated $225 million per year. Half of these savings would occur during peak load times.

- R&D in fundamental studies (deposition chemistry, device modeling, light extraction, and an optimum high-brightness capability of 200 lm/W);
- New manufacturing techniques, including better packaging, and lower costs; and
- A new lighting infrastructure, including sockets and fixtures, to light offices and whole metropolitan areas.

The Cost of a National Initiative

Dr. Bergh agreed with Dr. Haitz that reaching these goals would cost about $50 million per year for LEDs. To add OLEDs and to improve the lighting infrastructure would bring this figure to perhaps $80 million per year, for 10 years. Participants would be academia, industry, and government labs, with DOE as the lead agency. This plan also assumed that industry would provide matching funds—some in cash, some in kind. Among the benefits of such a program would be reduced energy consumption, better light, and a strong U.S. position in a major new industry.

In closing, Dr. Bergh reminded his audience that solid-state lighting is only part of the larger industry of optoelectronics, which includes optical communication, display, storage, solar cells, and lighting. An important theme is that all these growing industries are fed by the same technologies. Investment in a lighting program helps not only the lighting industry but it also provides indirect help for all the others. From the viewpoint of OIDA, the best investments are those with overlaps, synergies, and economies that benefit the spectrum of this rapidly emerging field.

LESSONS FROM EXTREME ULTRAVIOLET AND SEMATECH

David Attwood
Lawrence Berkeley National Laboratory

Dr. Attwood said that the light being discussed at the symposium embraced a broad range of wavelengths: from about 700 nanometers in the red to about 400 nanometers in the violet; computer chips that were made in ultraviolet at wavelengths of 248 nm and 193 nm; and extreme ultraviolet (EUV) lithography with wavelengths down to 13 nm. Topics had also included both refractive optics and reflective optics.

The New Extreme Ultraviolet Initiative

He described how a new initiative in EUV had emerged. It began with government support for basic research in several agencies, which made major contributions to early enabling technology; at the same time, two Stanford researchers developed a multilayer mirror. The lithography system works by shining a 13-nm light onto the mirror, which is made of multiple layers of molybdenum-silicon. The light reflects through a pattern of absorbers, an optical system reduces it by about 4:1, and the reflected light prints the final pattern.

An Industry-Driven Process

That effort evolved into a partnership consisting of three national labs (DOE, DOD through DARPA, and NIST through the Advanced Technology Program), universities, and some industries. The partnership developed further into a consortium involving primarily Lawrence Livermore, Sandia, and ATT Lucent, with help from the Advanced Technology Program. That consortium took the form of an industry-driven CRADA, funded for 5 years at $50 million a year. The industrial groups include Intel, Motorola, and AMD, later joined by Micron, Infineon, and a few weeks before the symposium by IBM. The national labs included Lawrence Livermore, Lawrence Berkeley, and Sandia. The companies were concentrating on the mask issue, with the rest of the work done by the three national labs. One major effort was to reduce the original quarter-micron technology by which the original Pentium chips were produced, to 70-60-50 nm patterns. These are still five years from production.

Competing research programs are reviewed by an industry-led and -dominated process run by SEMATECH for evaluating and comparing various next-generation lithography techniques. For the last six years, the coalition has had an annual meeting and semiannual smaller meetings.

Role of the National Labs

In the partnership, Sandia is responsible for overall integration, for the EUV source, and for resist recording material development. Lawrence Livermore is responsible for optics, coating, and making the mask blank. Lawrence Berkeley is responsible for EUV metrology and student training. Dr. Attwood said that this partnership was now beginning to work more smoothly as a coordinated activity.

Accelerating Some Goals

The semiconductor industry regularly updates its roadmap, which describes the anticipated capabilities for feature size, clock frequency (computing speed), etc. For example, some time ago the roadmap called for printing the first Pentium chip at 250 nm and 400 megahertz. Then it mapped anticipated progress to the year 2014, which called for chip frequencies in the gigahertz range, and examined the technologies, such as krypton fluoride and argon fluoride lasers, that might help the industry to get there.

The industry is now accelerating some of its goals. In the latest roadmap, 2014 has become 2013, and it further contemplates moving from a 3-year cycle to a 2-year cycle, thus potentially moving 2013 goals up to 2007. Suppliers have to promise the delivery of tools by 2007 to meet the new product requirements.

The next stage is commercialization. Now that the basic technology is developed and companies have chosen EUV lithography to etch the next generation of chips, the subsequent challenges are how to build the appropriate infrastructure and accelerate the training.

Closing Remarks

William Spencer
Washington Advisory Group

A REVIEW OF SEMATECH's ROLE

Dr. Spencer reviewed several elements of SEMATECH's development that were relevant to the needs of solid-state lighting. He said that in 1985, when SEMATECH was starting to be advocated, the U.S. semiconductor industry was in crisis and rapidly losing market share to foreign firms. Within a decade of initiating a government-industry partnership in the form of SEMATECH, it had come to understand the economic and scientific advantages of working together.

Cooperative activities started 1987 with the decision that the participating companies would contribute $100 million in cash; in-kind contributions were not accepted. This was matched by the federal government, mandated by Congress and supplied through DARPA. By 1994, SEMATECH had decided to end government support both because it had met its goals and because U.S. industry had returned to a position of relative strength. In 1995, it decided to become international and invited the main competitors of U.S. companies to join. Every region did decide to join except Japan, which initiated its own version of SEMATECH.

SOME LESSONS LEARNED

He summarized some of the lessons learned from the SEMATECH experience:

- **Recruit the best leaders.** From the beginning, the very best leaders of the semiconductor industry were involved.[3] Board members included the chief executive officers or key leaders of the major participating companies.

[3]SEMATECH directors included Robert Noyce, cofounder of Intel Corp.; Charles Sporck, CEO of National Semiconductor; and Robert Galvin, CEO of Motorola.

- **Convey your message publicly.** These industry representatives were sent early to explain the purpose and advantages of SEMATECH to leaders of the government and private sector.
- **Focus the program.** SEMATECH did not try to approach the entire semiconductor industry; rather, it focused its attention on the equipment industry, which was about one-fourth the size of the semiconductor industry. This stimulated a flow of money similar to the flow seen recently from the automobile industry to its suppliers.
- **Set measurable objectives.** In 1988, SEMATECH began creating roadmaps. Objectives were to advance generic and precompetitive knowledge. The consortium did not support product development or other competitive activities, which would have raised conflicts among members. By focusing on infrastructure, members could work together on methods and instrumentation that benefited all without compromising competitive positions.
- **Set uniform requirements.** Participating members were not allowed to reduce their dues by opting out of particular programs. Everyone joined every program, so that support was not fragmented.
- **Plan first, spend later.** Dr. Spencer said that SEMATECH got off to a slow start as it felt its way toward mission. In 1988, he said, the government and industry gave $200 million to "an immature organization in Austin" that was not yet prepared to spend those funds wisely; this required several years to learn. He advised all consortia to have their roadmaps in place before launching programs.

Consortium Accomplishments

What was accomplished? One way SEMATECH defined success was to increase its global market share through a stronger equipment industry. *The Economist* did a study after SEMATECH "declared success" in 1993, and despite the journal's general skepticism about government-industry partnerships, it concluded that an "amazing turnaround" had occurred in U.S. industry, and that some people were giving SEMATECH credit. Dr. Spencer added that SEMATECH's members recognized that "we were out of crisis mode," increased their private funding by 30 percent in 1994, and agreed that working together can bring economic advantages.

In addition, members found the consortium to be a valuable forum for exchanging information. At the outset, when assignees first joined SEMATECH, most of them had strict instructions not to reveal any information of their own but instead to learn as much as they could. After a short time they found that "all the participants already knew everything" about the other participants, "the locks disappeared from the filing cabinets," and a cooperative culture evolved. "One of the major things we learned," said Dr. Spencer, "was that even though the semiconductor industry is highly competitive, companies can work together to the benefit of all."

The roadmap developed in 1987-88 was expanded in 1991-92. It has proven to be a major asset for the entire industry. SEMATECH shared it with the world, and today the organization has over 1,000 engineers and scientists and an "evergreen" document maintained on the Web site at a cost of about half a million dollars a year.

DISCUSSION I

Mark Ginsberg
Department of Energy

Roadmapping Praise

Dr. Ginsberg, whose primary area of responsibility is energy efficiency, said that energy efficiency is not the only potential advantage to an LED industry. He praised the roadmapping process, and said that his department's Vision 2020 roadmap was an effort to bring an industrial perspective to an agenda that would allow government and industry to collaborate, as they have in other industries.

A roadmap should include short-, medium-, and longer-term perspectives, he said. Many people believe the department's role is to represent the high-risk, long-term, precompetitive perspective, but he suggested a variety of roles, including the reduction of information and policy barriers.

A Growing List of Applications

He described a "windows roadmap" for solid-state lighting, with the objective of creating active windows that are appliances within the wall. These active windows would provide all forms of information and entertainment, including educational material, news, and stock prices; a flick of a switch could change a representation of a cloudy day to a sunny day. "What I sense today," he said, "is appreciation for a technology that is going to have more and more applications as we look more closely. We're just touching on the edge of it." He recalled the earlier discussion of Thomas Edison's role in developing new technologies. Although Edison "may have been fortieth on a list of inventors for the original incandescent," he had the genius of seeing its potential for lighting and the imagination to implement the concept in ways that no one else did. In the same way, he helped to invent the film industry.

DOE's Role

Dr. Ginsberg said that DOE has a key role to play in implementing a solid-state lighting industry. The industry's roadmap fits his own division's mission (making buildings more efficient and affordable) and the mission of DOE (research, energy savings, and industry partnerships). The development of solid-state lighting and white-light applications can be perceived as precompetitive, longer-term objectives that help accelerate applications. The national laboratories have a long history in this area, familiar roles to play, and a track record of excellence and accomplishment. DOE's investment in solid-state lighting is still limited, but within the core capabilities of Sandia, Lawrence Livermore, and Lawrence Berkeley are people who can add to the effort significantly, even without a congressional budget line item for LEDs/OLEDs. Furthermore, he said, the department can channel R&D resources to move the effort forward.

How Industry Can Work with Government

Dr. Ginsberg read a quotation from Alan Bromley, former science advisor to President G.W.H. Bush: "Technological innovation depends on a steady flow of discovery by trained workers generated by federal science investments in universities and national laboratories. These discoveries feed directly into the industries that drive the economy. It's a straightforward relationship: industry is attentive to immediate market pressures, and the federal government makes the investments that ensure long-term competitiveness."

He said that this assertion applies to the optoelectronics industry, which was why he chose to participate in the symposium. "I'm absolutely confident," he said, "that working together we can advance the science and accelerate the applications of this very vital technology."

DISCUSSION II

Charles Becker
General Electric Corporate R&D

Industry's Need for Government Funding

Dr. Becker said that he spoke for General Electric, the country's largest lighting producer, in strongly supporting a U.S. lighting initiative. His company is pursuing both inorganic and organic LEDs and sees them both as large potential markets. At present they carry high-technology risk and require long-term R&D, for which "we can certainly use government funding to accelerate the work."

He said that GE's initial-market view, which is similar to that of the other major companies, is that they will include mostly specialty and monochromatic applications, "and we have a clear roadmap of how to get there." What is less clear, he said, is how to make the leap to the system level: how can the industry move from small lamps and demonstrations to practical systems that are part of the real world? This is where industry needs help.

The Need to Drive the Entire System

His company also sees this market as highly substitutable, that is, there are options other than LEDs for advanced lighting, but no others that can produce light as efficiently as LEDs. To penetrate the general lighting market and realize potential energy savings it is necessary to drive the entire system and promote the acceptance of LEDs not only by the lighting industry but also by the architectural and building industries.

An Informal Symposium Summary

He said he would offer a consensus of what had been said by symposium participants.

- **National opportunities.** Solid-state lighting has the potential to bring about a 50- to 90-percent reduction in lighting energy usage in the United States, with possibly $90 billion in savings and large reductions in emissions. New system opportunities can also be expected, such as integration with advanced building systems and controls. End users can anticipate lower life-cycle costs and drastically reduced maintenance. The national technology base would be strengthened by synergies for wide band-gap materials, an expanded R&D base, foreign investment in the United States, and synergies with the defense effort.
- **Economic opportunities.** For industry, LEDs have the potential of being a multibillion-dollar domestic industry, both complementary with and disruptive to existing incandescent and fluorescent systems. Lighting manufacturers can anticipate high-growth products, which holds great interest in an industry that typically grows by 3 percent annually. The nation would benefit by increased high-technology employment and global competitiveness.
- **Challenges.** Development of an LED lighting industry would require technological breakthroughs on several fronts: a reduction in costs by a factor of about 50; a 10-fold improvement in efficiencies; a 50- to 500-fold improvement in total lumen output. Broader challenges include the development of standards (sockets, measurement techniques and standards, integration with building systems), a mass manufacturing infrastructure, and the education of end users.

He diagnosed the current R&D base as healthy and characterized by great progress in the national labs and universities. Because of this foundation, he said, industry could probably commercialize solid-state lighting on its own, but foreign firms that are being actively supported by their governments would almost surely surpass it.

Costs Must Be Lower

Initial costs must be low to drive acceptance, a lesson learned with great difficulty in the compact fluorescent market. He reemphasized the key importance of cost: "At 50 cents a lumen, we're not playing in the market with any other lighting technology. Fluorescents are well under half a cent per lumen, so we have a long way to go."

Areas for Collaboration

He described several areas for collaboration, all of which require long-term, precompetitive R&D:

- **Standards.** Metrology, socket definition, electrical supplies, control interfaces, color, and consumer education.
- **Materials.** Epitaxial growth with fewer defects; chip fabrication and structure for light extraction; heat management; phosphors and phosphor deposition; organic materials for OLEDs and device design for efficient light extraction from the OLEDs; encapsulance, both in OLEDs and inorganic LEDs; light-management materials and systems; and thermal management materials and systems.
- **Manufacturing.** Reactors for epitaxial growth; high-volume organic sheet manufacturing for large areas; lamps; high-performance, low-cost packaging, an area that is not a particular strength in this country; and low-cost electronics to convert LED lamps to standard 110-volt wiring.
- **Applications.** Collaboration with the architectural design and construction industries; efficient overall optical design to deliver light where it is needed; human factors; and fixtures.

A "Straw Man" for the Future

Finally, he suggested a "straw man" picture of the future. He began with the need to evolve and expand existing OIDA working groups and to build more cooperation with the national labs (especially DOE and NIST) and universities, as well as with other industry bodies, such as the National Electrical Manufacturers Association, Electric Power Research Institute, and international consortia. This plan recognizes the reality that all major lighting manufacturers are now global companies. Beyond that, he sees the need to clearly identify areas of precompetitive technology, formulate a roadmap and a formal budget, and identify opportunities to drive initial acceptance of LED products. "They're not likely to fly off the shelves if we just put them out there," he concluded. "We need to create the market and then publicize it."

Why Should LEDs Do Better Than Compact Fluorescents?

Leslie Levine said that his company, Fusion Lighting, was supported by DOE to develop an electrode-less light source with long life and high efficacy. He said that many of the challenges described during the symposium related to his company as well. Compact fluorescents were introduced 20 years ago and have met with only moderate success despite their high efficacy; he asked why LEDs might be expected to do any better.

Dr. Becker said that General Electric believed that price was the most important issue; for example, it is possible to convince a large retailer or hotel chain to buy efficient lighting, but the residential market is a difficult sell. It is essential to drive the unit costs of LEDs down to a level comparable to those of existing technologies.

Dr. Bergh called Mr. Levine's reasoning "a trap": The objective, he said, should not be to develop an application that provides only a one-to-one replacement of the light bulb. Instead, the goal should be to usher in a wholly new lighting industry. He suggested two thrusts: (1) gradual replacement of lighting functions, and (2) simultaneous emergence of a new lighting paradigm that is recognized as different and attractive because of its low cost, flexible adjustment of the light spectrum, long lifetime, and minimal space requirements. This paradigm might be applied initially to new buildings and architectural installations but would gradually create a new industry that could move beyond the replacement of streetlights and signs toward the general lighting market.

Leveraging Ongoing Work

John Zolper of the Office of Naval Research said that his organization shared some of the interests described in the symposium, especially materials for the wide band-gap area, and suggested leveraging R&D investments already made, particularly in forming substrates and the growth of active device layers. Although the Navy effort might have "different flavors," he said, many of the challenges would be similar and it made sense to coordinate research activities.

SEMATECH's Focus on Infrastructure

A questioner asked how much of SEMATECH's success could be attributed to supported infrastructure rather than process or design work. "One hundred percent," answered Dr. Spencer. "Focusing on infrastructure was the key." He said it was also the reason current members had stayed. Today a manufacturing facility costs approximately $2 billion, with equipment costs representing 75 percent of that. If a company's engineers have the opportunity to work with that equipment, they are less likely to make a mistake when they buy their own etching or deposition or lithography equipment. This can bring them a return worth many times their dues. He reiterated that much of SEMATECH's success came from directing money to its suppliers for precompetitive work that did not provoke antitrust problems.

Another participant noted that SEMATECH had a clearer challenge in designing a consortium because the research path was more sharply defined. In the optoelectronics industry much of the basic science is not yet understood. Dr. Bergh replied that the semiconductor experience provides a good lesson for the optoelectronics industry, which is about 30 years behind. He said that the only difference was one of timing. "It takes a new idea about 20 years to become an overnight success," he said. Optoelectronics is perhaps 5 to 10 years from the point when SEMATECH was formed. When it reaches that point, it will be able to use what SEMATECH has taught.

Integrated Circuits Versus LEDs

Dr. Haitz noted a crucial difference between the integrated circuit industry and the LED industry. In integrated circuit work there is a common infrastructure: all companies buy the same equipment and use the same feature size. Differentiation comes in product design. For LEDs the epitaxial process is one crucial step where companies try to differentiate themselves; another is the LED substrate and the gas supply that goes into the epitaxial process. This, he said, makes it more complicated to follow the SEMATECH model. He was hopeful, however, that there would be common areas that could be adapted to the model. An important step is to find precompetitive areas and define them so that there is also room to compete.

Dr. Spencer agreed with that point, but added that the semiconductor industry is divided as well. Some companies work on what is called the "bleeding edge," the risky arena of buying new equipment and building large, expensive fabrication plants. One and two decades ago the memory manufacturers populated the bleeding edge. Over the last 10 years the microprocessor manufacturers moved into this space. A large part of the industry resembles the LED industry: the part that is buying equipment that has resolution capability of only 1 to 2 microns, rather than the 150 nm discussed in the EUV program.

He suggested that one way to avoid the problem of different interests is to adopt the model of the Semiconductor Research Corporation (SRC), which is a much smaller activity that preceded SEMATECH by five years and funds only university-based research. At the outset the SRC's main purpose was to ensure a supply of trained graduates, but it now supports some research aimed at the barriers that the semiconductor industry is going to face when it begins to encounter quantum effects on very narrow gates and when it goes beyond the use of copper as an interconnect. In other words, it now funds longer-range, mission-oriented research in universities aimed at solving particular R&D problems.

Concluding Points on a National Initiative . . .

Dr. Wessner recalled Dr. Spencer's reference to "selling" SEMATECH when the industry, despite its military importance, was under great threat. Members of the optoelectronics industry also face the challenge of trying to sell an opportunity and a somewhat distant threat.

A second issue is the desire to form quickly a U.S. consortium to help U.S firms become competitive in the global market. In today's global economy the major lighting companies are international, and consortia tend to be international as well. SEMATECH solved that in two stages, moving from a national to an international stance. One could argue in favor of forming an international consortium once a position of strength has been achieved.

He reemphasized the importance of industry leadership and persistence. During the mid-1980s, the government was opposed to the idea of SEMATECH, and a sustained effort by Clark McFadden and many others from the private and public sector was required to convince government leaders to support a partnership.

A final challenge is how to create a new industry for general lighting in parallel with a second effort to transform building and architectural lighting. Again, the initiative of private industry in providing funds for the Semiconductor Research Corporation may be relevant. Although the private sector should not be alone in taking such initiatives, it may be that innovations must begin there.

. . . and a Final Note of Optimism

Dr. Spencer echoed a point made earlier by Dr. Trimble. A government-industry partnership is best shaped by not restricting the natural innovative energy of private firms. Valuable collaborations can be created between ongoing research programs in government labs and federally funded, university-based R&D. He suggested a strong effort to leverage programs that now exist and to include private funding mechanisms, including venture capital firms. He concluded the symposium on a note of optimism, suggesting that both the private and government sectors had showed the ability and willingness to create the productive collaborations needed to bring solid-state lighting to a far larger marketplace.

III

APPENDIXES

Appendix A: Speaker Biographies

DAVID ATTWOOD

David Attwood is currently Director, Center for X-Ray Optics at the Lawrence Berkeley National Laboratory in Berkeley, California, and was Scientific Director, Advanced Light Source until 1988. He has held a position in the College of Engineering at the University of California at Berkeley, as Professor in Residence for Applied Science and Technology since 1989 and for Electrical Engineering and Computer Science since 1993. He also held positions in the Department of Applied Science at the University of California at Davis from 1978-1983 and at Lawrence Livermore National Laboratory from 1972-1983, ultimately serving as Deputy Associate Program Leader for the Fusion Experiments Program prior to moving to Berkeley. He also held a position as Research Scientist at General Applied Science Laboratories from 1965 to 1968.

Dr. Attwood is a member of the American Physical Society, Optical Society of America, American Association for the Advancement of Science, Sigma Xi, Canadian Institute for Synchrotron Radiation, and the Japanese Society for Synchrotron Radiation Research.

He holds a B.S. in Engineering Science from Hofstra University, an M.S. in Astronautical Sciences from Northwestern University, and a D.Eng.Sci in Applied Physics from New York University.

CHARLES BECKER

Dr. Becker is the Manager of LED Projects at General Electric Corporate Research and Development, including advanced research supporting brightness LED and LED systems development. Key technologies under investigation consist of phosphors, high-performance encapsulation materials, high power packages, and system integration.

In previous GE assignments he managed the development of CMOS IC processes and characterization, high-performance electronic packaging, power control systems, and a broad array of technologies supporting GE's industrial businesses. During 1997 he was a key architect of the GE corporate Design for Six Sigma engineering initiative.

Dr. Becker received his Ph.D. in Physical Chemistry at the University of Chicago in 1979. He has been a member of the Board of Visitors of Duke University's School of Engineering and of the Executive Advisory Board of the RPI Center for Integrated Electronics. He has authored 10 papers and 1 book chapter and holds 5 U.S. patents.

ARPAD BERGH

Arpad A. Bergh received his Ph.D. from the University of Pennsylvania in 1959 in Physical Chemistry. From 1959 to 1984 he was with Bell Laboratories. In 1968 he became head of the Compound Semiconductor Materials and Devices Development Department in Murray Hill, N.J., responsible for lasers, LEDs, photodetectors, and microwave devices.

When Bellcore was formed in 1984, Dr. Bergh became Division Manager of the Device Science and Technology Research Division, conducting research in photonic devices, gallium-arsenide high-speed circuits, and display devices. In 1986 he became Executive Director of the Applied Research Program Department responsible for strategic planning and customer interface maintenance.

In 1994 he retired from Bellcore to become the full-time president of the Optoelectronics Industry Development Association (OIDA) in Washington, D.C. OIDA is an industry association of the major players in the North American optoelectronic industry. Affiliate members include university centers doing research in optoelectronics.

Dr. Bergh holds 11 patents and has authored over 20 papers on semiconductor materials and devices. He has coauthored *Light Emitting Diodes* (Oxford Press, 1976) and several book chapters on Network Systems Applications and Markets for Optoelectronic Integration. He is a fellow of the IEEE and member of OSA and SPIE.

KAREN H. BROWN

Dr. Karen H. Brown is the National Institute of Standards and Technology's acting director and deputy director. As a non-regulatory agency of the U.S. Department of Commerce's Technology Administration, NIST's mission is to strengthen the U.S. economy and improve the quality of life by working with industry to develop and apply technology, measurements, and standards through a portfolio of four major programs: the NIST Laboratories, the Baldrige National Quality Program, the Manufacturing Extension Partnership, and the Advanced Technology Program. Brown oversees an $800-million annual operating budget and 3,300 onsite staff complemented by 2,000 manufacturing and business specialists serving smaller manufacturers around the country. Effective January 21, 2001, Dr. Brown was designated to serve as Acting Under Secretary for Technology of the Commerce Department's Technology Administration.

She came to NIST as deputy director in January 1999. Previously she was a Distinguished Engineer at IBM Microelectronics in Hopewell Junction, N.Y. Dr. Brown also served (on assignment from IBM) as director of lithography for SEMATECH from 1994 to 1998. During her 22-year career at IBM she concentrated on solving problems in semiconductor lithography and microelectronics. She has a proven track record in management, having successfully met the challenges of moving ideas from the laboratory into manufacturing. She also has a keen awareness of the impact of national and international standards on U.S. industry and the economy, having held a variety of standards leadership positions in Semiconductor Equipment and Materials International and helping to bring a semiconductor fabrication line on board in France.

A native of Schenectady, N.Y., Dr. Brown holds a B.A. in chemistry and in history and a Ph.D. in chemistry from the University of Rochester.

MAKARAND CHIPALKATTI

Dr. Chips Chipalkatti is marketing and technical manager for LED Light Sources and is responsible for starting up and managing OSRAM Sylvania's LED lamp modules business for General Lighting, in collaboration with sister concern OSRAM Opto Semiconductors. Prior to his current position, Dr. Chipalkatti led OSRAM Sylvania's OLED research and development, and worked on projects involving optical polymers, molecular semiconductors, and automotive and electrical applications. He began his career at GTE Laboratories, Inc., working with polymers in automotive, electronics, lighting applications and in fiber optics.

He holds a Ph.D. in Polymer Science and Engineering from the University of Massachusetts; an M.S. degree in Chemical Engineering from Michigan Technological University; and a B.S. in Chemical Engineering from the Indian Institute of Technology in Bombay.

M. GEORGE CRAFORD

M. George Craford is the Chief Technology Officer of LumiLeds Lighting. He obtained a BA degree in Physics from the University of Iowa in 1961 and a Ph.D. degree in Physics from the University of Illinois in 1967. Dr. Craford began his professional career as a research physicist at Monsanto Chemical Company. Initially, his research dealt with the development of optoelectronics materials and devices using a variety of compound semiconductor materials. In 1974 he became the Technical Director of the Monsanto Electronics Division with management responsibility for silicon wafer development as well as compound semiconductor materials and device development. In 1979 Dr. Craford joined Hewlett-Packard Company as manager in the Optoelectronics Division, responsible for the development of technology and processes for manufacturing visible light emitting diodes. In 1999 Dr. Craford assumed his current position as Chief Technical Officer of LumiLeds Lighting, a joint venture of Agilent Technologies and Philips Lighting.

Dr. Craford first became known for the development of nitrogen-doped GaAsP technology for yellow and red-orange LEDs at Monsanto in the early 1970s. This became one of the dominant commercial LED technologies. At Hewlett-Packard his group maintained a leadership position in LED performance and production technology with the introduction of red and yellow AlInGaP devices, grown by MOCVD, which have better luminous efficiencies than incandescent lamps. These devices are widely used in such outdoor applications as traffic signals, highway signs, and automotive lighting. He was also responsible for programs that developed InGaN technology for blue and green emitters.

Dr. Craford is a member of the National Academy of Engineering and a Fellow of the IEEE. He has received the MRS Medal, the IEEE Morris N. Liebmann Award, the Holonyak Award of the Optical of America, the Welker Award of International Symposium on Compound Semiconductors, the Electronics Division Award of the Electrochemical Society, and the Distinguished Alumni Award of the University of Illinois College of Engineering. He has published over 50 papers and book chapters, has given invited and plenary talks at a variety of conferences, and holds several commercially important patents.

STEVEN DENBAARS

Steven DenBaars is a Professor of Materials at the University of California at Santa Barbara (UCSB) and is also a member of the Scientific Advisory Board at Cree Lighting, Inc. From 1988 to 1991 Prof. DenBaars was involved in the fabrication of high-brightness LEDs as a member of the technical staff at Hewlett-Packard. In 1991 he joined the UCSB faculty, where he is developing new solid-state optoelectronic devices. In 1996 he cofounded Nitres, Inc., (which was acquired by Cree in May 2000) to commercialize solid-state lighting products. His research involves MOCVD growth of GaN- and InP-based vertical cavity lasers, tunable lasers, and detectors. Special interests include the effect of materials properties on device performance blue VCSEL lasers and microwave power transistors. He has received a National Science Foundation young investigator award (1995) and the Young Scientist Award from the International Symposium on Compound Semiconductors in 1998. He has served on two Department of Defense committees surveying wide band-gap semiconductor technology in Europe and Japan in 1998 and 1999. Currently, he is an associate director of the solid-state lighting and display center at UCSB, which is developing new more energy efficient light sources. He has written over 240 technical publications, 3 book chapters, and 100 conference presentations, and has been granted 7 patents.

STEVEN J. DUCLOS

Steven Duclos manages the Electronic and Optical Materials program at the General Electric Corporate Research and Development Center in Niskayuna, New York. The program is responsible for development of advanced electronic and optical materials for General Electric's Lighting and Medical Systems Businesses. This includes OLED device development for general illumination, phosphors for both solid-state and conventional lighting products, and scintillators for X-ray detection in both Computed Tomography and Positron Emission Tomography. The program also develops transparent ceramic materials for advanced high-intensity lighting technologies. In addition to his work on luminescent materials Dr. Duclos has also contributed to developments in the growth of synthetic diamonds at high pressure and temperature, and processes for materials purification using luminescence detection techniques. Prior to joining the GE Corporate Research and Development Center he worked on C_{60} superconductivity at AT&T Bell Laboratories in Murray Hill, New Jersey.

Dr. Duclos received his B.S. degree in Physics in 1984 from Washington University in St. Louis; an M.S. degree in Physics from Cornell University in Ithaca, New York, in 1987; and a Ph.D. in Physics from Cornell in 1990. He is the recipient of an AT&T Bell Laboratories Predoctoral Fellowship and the 1997 Albert W. Hull Award, GE Corporate R&D's highest award for early career achievement.

KATHARINE B. GEBBIE

Katharine Blodgett Gebbie is Director of the National Institute of Standards and Technology's Physics Laboratory, which supports U.S. industry, government, and the scientific community by providing measurement services and research for electronic, optical and radiation technologies. Its focus on atomic, molecular, optical and radiation physics reflects the continuing importance of these disciplines in developing new measurement technology.

Dr. Gebbie graduated from Bryn Mawr College with a B.A. degree in physics and subsequently earned a B.S. degree in astronomy and a Ph.D. in physics from University College, London. She joined NIST in 1968 as a physicist in the Quantum Physics Division of JILA, a cooperative enterprise between NIST and the University of Colorado in Boulder. She has worked extensively on the physics of the solar and stellar atmospheres. Before being appointed Director of the newly formed Physics Laboratory in 1991, she served as Chief of the Quantum

Physics Division and Acting Director of the Center for Atomic, Molecular and Optical Physics.

She is a Fellow of the American Physical Society, a Fellow of JILA, and a member of several professional societies, including Sigma Xi and American Women in Science. She has served as Vice President of the International Committee on Weights and Measurers and as President of the Consultative Committee on Temperature. She has received several awards, including the Department of Commerce Gold Medal, the Women in Science and Engineering (WISE) Lifetime Achievement Award, and the Washington Academy of Sciences Award for Outstanding Contributions to the Physical Sciences.

MARK GINSBERG

Mark Ginsberg is Deputy Assistant Secretary for the Office of Building Technology, State and Community Programs (BTS) in the Department of Energy. In that position Mr. Ginsberg oversees a comprehensive set of programs to make buildings, equipment, and appliances more energy efficient; support state, community, and low-income energy programs; and pave the way for a healthy and prosperous future through high-efficiency research and development, building codes, and appliance standards. With a staff of 80 and a budget request of $300 million for fiscal year 2001, BTS utilizes partnerships with industry, states, national energy laboratories, universities, DOE's field structure and regional offices to strengthen and leverage its capabilities.

From December 1991 until July 1997 he directed the Federal Energy Management program, which leads the federal government's effort to reduce its energy consumption by 30 percent and which can save American taxpayers $1 billion every year.

Prior to joining DOE in 1991 Mr. Ginsberg served as Director of the Arizona Energy Office, where he earned a reputation for aggressive energy policy, solar and community energy programs, emergency preparedness, and economic development. He helped found and served as a board member and officer of the National Association of State Energy Officials. He chaired the Western Interstate Energy Board and served on the Board of the Interstate Solar Coordination Council, forerunner of the Interstate Renewable Energy Council.

DAVID J. GOLDSTON

David Goldston was appointed staff director of the House Committee on Science in January 2001. As such, he oversees a committee with jurisdiction over most of the federal civilian research and development budget, including programs run by NASA, the National Science Foundation, Department of Energy, Department of Commerce, and the Environmental Protection Agency. Prior to becoming staff director Mr. Goldston was legislative director for Congressman

Sherwood Boehlert (R-NY), who became chairman of the Science Committee in January 2001. Congressman Boehlert is a leading moderate Republican and has led efforts to protect the environment; Mr. Goldston was his top environmental aide and also oversaw the legislative and press operations of the office.

Mr. Goldston came to Capitol Hill in 1983 as Boehlert's press secretary. From 1985 to 1994 he served on the Science Committee as the special assistant on the Subcommittee on Science, Research, and Technology. In that role he oversaw the programs of the National Science Foundation and the National Institute of Standards and Technology and also directed the congressman's efforts to shut down the superconducting supercollider (SSC). In 1994 and 1995 Mr. Goldston was project director at the Council on Competitiveness, a private-sector group with members from industry, labor, and academia. He directed work on the report "Endless Frontier, Limited Resources: U.S. R&D Policy for Competitiveness."

Mr. Goldston was graduated magna cum laude with a B.A. in American history from Cornell University in 1978. He has completed the course work for a Ph.D. in American history at the University of Pennsylvania.

ROBERT KARLICEK

Dr. Karlicek is the Director of LED Technology for GELcore LLC. He manages the development of high-brightness LED lamp development at GELcore, a joint venture of General Electric Lighting and EMCORE. Management responsibilities include the development of high-brightness LEDs in conventional packaging formats as well as the development of advanced technologies for future illumination applications. Prior to GELcore Dr. Karlicek was at EMCORE, where he started in 1996 as a Senior Staff Scientist and subsequently assumed lead responsibility for the development of GaN- and AlInGaP-based high-brightness LED technology, including reactor development, LED device design, and technology transfer to manufacturing. Prior to joining EMCORE Dr. Karlicek spent 16 years as a member of technical staff at AT&T Bell Laboratories, where his responsibilities included basic and applied research on a variety of crystal growth techniques used to fabricate laser diodes for telecommunications applications. Dr. Karlicek's technical contributions include over 40 authored or coauthored papers in peer-reviewed technical journals, and he holds 8 U.S. patents.

SHEILA KENNEDY

Sheila Kennedy is a founding principal of Kennedy & Violich Architecture, an interdisciplinary design practice that explores relationships between architecture, technology, and contemporary life to develop new ways to organize program activities and space. Kennedy & Violich Architecture is a nationally recognized leader in the design of new applications for recycled materials, and the creation of electro-conductive and luminous materials that are applied in built projects. Kennedy & Violich Architecture works collaboratively with industrial manufacturers, scientists, business leaders, artists, educators, and public agencies to define problems, propose projects, and create and realize architecture that supports client identity and institutional mission. The firm's recent built work in architecture includes a luminous Archeology Museum under an Interstate Highway, an Elementary School Library with a bookshelf and data system that integrates books with information technology, a Dance Theatre with a shiny, sensuous, sound-absorbing building skin, and an electrified plywood floor that transforms into a high-tech desktop in a Gallery for Contemporary Art. Selected projects and material research are presented at <www.kvarch.net>.

Sheila Kennedy combines practice with teaching. As Associate Professor at the Harvard University Graduate School of Design, she was the Director of the M Arch II Advanced Design Program from 1992 to 1996. She has received national recognition for her research and built work in design, including grants from the National Endowment for the Arts, an Interdisciplinary Award from Progressive Architecture, and six National Honor Awards for Design Excellence from the American Institute of Architects. The work of Kennedy & Violich has been exhibited at the San Francisco Museum of Modern Art, the Museum of Modern Art in New York, the Architectural League of New York, and the Wexner Center for Contemporary Art in Ohio. The work of Kennedy & Violich Architecture has been published internationally in many architecture journals, as well as in *Art in America, Time Magazine*, *The Wall Street Journal, Wired,* and *The New York Times*. Projects by Kennedy & Violich Architecture appear in the collection *10x10* (Phaidon, 2000) and *New American Architects* (Thames & Hudson, 2001). In 2000 the Architectural Association of London published a monograph on Kennedy's work and writings on design in a book titled *Material Misuse*.

CLARK McFADDEN

Mr. McFadden specializes in international corporate transactions, especially the formulation of joint ventures, consortia, and international investigations and enforcement proceedings. Mr. McFadden has had a broad background in foreign affairs and international trade, having experience with congressional committees, the U.S. Department of Defense, and the National Security Council.

In 1986 he was appointed general counsel to President's Special Review Board to investigate the National Security Council system (Tower Commission). In 1979 Mr. McFadden served as Special Counsel to the Senate Foreign Relations Committee on the Strategic Arms Limitation Treaty (SALT II). From 1973 to 1976 he worked as General Counsel, Senate Armed Services Committee, and was responsible for all legislative, investigatory, and oversight activities. Mr. McFadden has a B.A. from Williams College (1968), an M.B.A. from Harvard University (1972), and a J.D. from Harvard Law School (1972).

ALTON D. ROMIG, JR.

Dr. Alton D. Romig, Jr., is Vice President for Science & Technology and Partnerships and Chief Technology Officer at Sandia National Laboratories, Albuquerque, New Mexico. He is Chief Scientific Officer for the Nuclear Weapons program. He is also accountable for Sandia's interactions with industry and the laboratories' Campus Executive Program. In addition he is responsible for the Laboratory Directed Research & Development program (DOE's IR&D). Dr. Romig's responsibilities include the leadership and/or management of research, development, and engineering in nanosciences, materials and process sciences, microelectronics/microsystems and optoelectronics, advanced manufacturing, computational sciences, modeling and simulation science, and high-energy density physics.

Dr. Romig has approximately 160 technical publications, is the coauthor of 3 textbooks, and holds 2 patents. He is a past president of ASM, International (formerly American Society for Metals). He is currently the Chair of the ASM Educational Foundation. Other current professional activities include serving on and chairing a number of committees for ASM International; the Minerals, Metals, and Materials Society; the Materials Research Society; and the Microbeam Analysis Society (MAS). He is active on a number of National Academy of Engineering/National Research Council Committees and Boards. He also serves on the Boards of Technology Ventures Corporation, a Lockheed Martin subsidiary dedicated to technology commercialization, and the National Coalition for Advanced Manufacturing (NACFAM).

For his pioneering work in analytical electron microscopy and solid state diffusion, Dr. Romig has received several awards, including the Burton Medal (1988), awarded by the Electron Microscopy Society of America to an Outstanding Young Scientist; the K.F.J. Heinrich Award (1991), given by the Microbeam Analysis Society to an Outstanding Young Scientist; the ASM Silver Medal for Outstanding Materials Research (1992); and the Acta Metallurgica International Lectureship (1993-94).

He received his B.S., M.S., and Ph.D. degrees in materials science and engineering from Lehigh University in 1975, 1977, and 1979, respectively. In 1979 he joined Sandia National Laboratories as a member of the technical staff in the Physical Metallurgy Division. After a variety of management assignments he was named Director, Materials and Process Sciences in 1992. In 1995 he was named Director, Microelectronics and Photonics, and in 1998 Director of Microsystems Science, Technology and Components. He served in this capacity until attaining his present position in 1999.

BILL SPENCER

William J. Spencer was named Chairman Emeritus of the International SEMATECH Board in November 2000 after serving as Chairman of the

SEMATECH and International SEMATECH Boards since July 1996. He came to SEMATECH in October 1990 as President and Chief Executive Officer. He continued to serve as President until January 1997 and CEO until November 1997. During this time, SEMATECH became totally privately funded and expanded to include non-U.S. members. Many gave SEMATECH part of the credit for the U.S. semiconductor turn around in the 1990s.

Spencer has held key research positions at Xerox Corporation, Bell Laboratories, and Sandia National Laboratories. Before joining SEMATECH in October 1990, he was Group Vice President and Senior Technical Officer at Xerox Corporation in Stamford, Connecticut from 1986 to 1990. He established new research centers in Europe and developed a plan for Xerox retaining ownership in spinout companies from research.

Prior to joining the Xerox Palo Alto Research Center (PARC) as manager of the Integrated Circuit Laboratory in 1981 and as the Center Manager or PARC in 1982 to 1986, Spencer served as Director of Systems Development from 1978 to 1981 at Sandia National Laboratories in Livermore and Director of Microelectronics at Sandia National Laboratories in Albuquerque from 1973 to 1978, where he developed a silicon processing facility for Department of Energy needs. He began his career in 1959 at Bell Laboratories.

Spencer received the Regents Meritorious Service Medal from the University of New Mexico in 1981; the C.B. Sawyer Award for contribution to "The Theory and Development of Piezoelectric Devices" in 1972; and a Citation for Achievement from William Jewell College in 1969, where he also received an Doctor of Science degree in 1990. He is a member of the National Academy of Engineering, a Fellow of IEEE, and serves on numerous advisory groups and boards. He was the Regents Professor at the University of California in the spring of l998. He has been a visiting professor at the University of California at Berkeley School of Engineering and the Haas School of Business since the Fall of 1998. He is a Research Professor of Medicine at the University of New Mexico.

Dr. Spencer received an A.B. degree from William Jewell College in Liberty, Missouri, an M.S. degree in mathematics and a Ph.D. in physics from Kansas State University.

MARK THOMPSON

Mark Thompson graduated from the University of California at Berkeley in 1980 and from the California Institute of Technology with a Ph.D. degree in chemistry in 1985. He then took an S.E.R.C. postdoctoral fellowship with Prof. Malcolm Green in the Inorganic Chemistry Laboratory at Oxford, working on projects involving layered organometallic materials and the study of new materials for nonlinear optics. In 1987 Thompson joined the faculty of the Chemistry Department at Princeton as an Assistant Professor and in June of 1995 took and Associate Professor's position in the Department of Chemistry at the University of Southern California. In 1998 he was promoted to full professor in the Chemistry department at USC.

Thompson's research interests span a wide range, involving the syntheses, properties and structures of organic and metal/organic compounds. He has an active program focused on the synthesis and study of molecular and polymeric compounds for optical applications, particularly electroluminescence, as well as studying electron and energy transport in molecular solids. The photophysical properties of layered materials and their use in solar energy conversion are also very important in his work. His group has made a number of important advances in the design and fabrication of organic LEDs and solar cells. They were the first to demonstrate organic LED that efficiently utilizes phosphorescence, giving the devices efficiencies > 25 percent and have now demonstrated OLEDs with efficiencies close to 100 percent. They have prepared a novel stacked LED that gives full-color tunable emission from a single stacked R-G-B pixel, as well as transparent and flexible LEDs with high brightness and lifetime. All of these advances represent a close connection between the chemistry and engineering of these devices, in that both the architecture of the device and the tuning of the materials used to fabricate it are crucial and must be done in concert. The work in solar cells is focused on developing systems that can be used in direct photoelectrochemical processes. The thin film materials they are investigating are grown from aqueous solution and have good quantum yields (electrons out, photons absorbed). This is also a very materials-intensive project, with the optimal thin films being composed of three to four different donor and acceptor molecules, carefully chosen so that both electrical and energetic gradients are formed in the multilayer film.

CHARLES TRIMBLE

As one of the founders and as President, Chief Executive Officer, and currently Vice-Chair, Charles R. Trimble strategically guided Trimble Navigation to its dominant role in the GPS (Global Positioning System) information technology market. Prior to founding Trimble Navigation Mr. Trimble was manager of Integrated Circuit Research and Development at Hewlett-Packard's Santa Clara Division. During his tenure at HP, he was recognized for developing commercial advances in efficient signal processing, high-speed analog-to-digital converters and digital time-measurement techniques to the picosecond level.

Mr. Trimble received his B.S. degree in Engineering Physics, with honors, in 1963, and his M.S. degree in Electrical Engineering in 1964 from the California Institute of Technology. He was a member of the Vice-President's Space Advisory Board's task group on the future of U.S. Space Industrial Base for the National Space Council. In September of 1994 Mr. Trimble was honored with the Piper General Aviation award from the American Institute of Aeronautics (AIAA) for pioneering the manufacture and application of affordable GPS.

STEVE VAN SLYKE

Steve Van Slyke received his B.S. in Chemistry at Ithaca College and an M.S. in Materials Science at RIT. Mr. Van Slyke joined Eastman Kodak in 1979 and is a co-inventor of organic thin film electroluminescence. He has been active in all phases of organic electroluminescence research and development and is currently leading several programs that are developing high-volume manufacturing techniques for organic light emitting diodes (OLEDs). A leading authority on OLED technology, Mr. Van Slyke has published and presented over 20 papers and holds 14 patents in the areas of OLED materials and device architecture.

CHARLES W. WESSNER

Having served with three federal agencies in positions of increasing responsibility, Dr. Wessner brings a unique perspective on Washington policy developments and international cooperation. He also has extensive overseas experience, both as an international civil servant with the OECD and as a senior officer with the U.S. Diplomatic Corps. Since joining the National Research Council, the operational arm of the U.S. National Academy of Sciences, he has led several major studies, has a rapidly growing list of publications, and works closely with the senior levels of the U.S. government.

His work focuses on the linkages between science-based economic growth, new technology development, and international investment and trade in high technology industries. Recent work encompasses a White House-initiated study on U.S. aerospace competitiveness and a review of international competition and cooperation in high-technology industry. Currently, he directs a portfolio of activities centered around government measures to support the development of new technologies which have contributed to the New Economy. Projects now under way include Government-Industry Partnerships, including a Congressionally-mandated study of the Small Business Innovation Research Program, and a major project on Measuring and Sustaining the New Economy.

Dr. Wessner frequently testifies before congressional committees interested in STEP's work and most recently briefed congressional staff on the largest independent assessment of the SBIR program resulting from the Partnerships Program. Dr. Wessner also testifies before national commissions such as the U.S. Trade Deficit Review Commission and the Aerospace Offsets Commission. He lectures frequently at such universities as Harvard, College of William & Mary, George Mason, Georgetown, George Washington, Nottingham, Potsdam, and Helsinki University of Technology, as well as the ZEW in Mannheim, Sandia National Laboratories, and the Foreign Service Institute of the Department of State.

PATRICK WINDHAM

Until April of 1998, Mr. Windham served as Senior Professional Staff Member for the Subcommittee on Science, Technology, and Space of the U.S. Senate's Committee on Commerce, Science, and Transportation. He helped the senators oversee and draft legislation for several major civilian R&D agencies with responsibility for science, technology, and U.S. competitiveness; industry-government-university R&D partnerships; state economic development; federal laboratory technology transfer; high-performance computing; and computer encryption. From 1982 to 1984, he served as a legislative aide in the personal office of Senator Ernest Hollings. From 1976 to 1978, he worked as a Congressional fellow with the Senate Commerce Committee, and then returned to California from 1978 to 1982 to complete doctoral course work and exams in political science at the University of California at Berkeley. Mr. Windham holds a Masters of Public Policy from the University of California at Berkeley and a B.A. from Stanford University. He is currently an independent, California-based consultant on science and technology policy issues and an adjunct professor at Stanford University.

Appendix B: Participant List* March 2001 Conference

Alan Anderson
National Research Council

David Attwood*
Lawrence Berkeley National Laboratory

Sam Baldwin
Department of Energy

Norman Bardsley
Lawrence Livermore National Laboratories

Filbert Bartoli
National Science Foundation

Charles Becker*
General Electric

Arpad Bergh*
Optoelectronics Industry Development Association

Gary Brodersen
System Planning Corporation

James Brodrick
Department of Energy

Karen Brown*
NIST

John Carrano
DARPA

Chips Chipalkatti*
OSRAM Sylvania

McAlister Clabaugh
National Research Council

Camille Collett
National Research Council

George Craford*
LumiLeds Lighting

*Speakers

Daniel Dapkus
University of Southern California

Gordon Day
NIST

Steven DenBaars*
CREE and University of California at Santa Barbara

David Dierksheide
National Research Council

Steve Domenik*
Sevin Rosen Funds

Steve Duclos*
General Electric

Michael Dunn
Cree Lighting

Robert Eagan
Sandia National Laboratories

David Eaton
Dupont iTechnologies

Pamela Farrell
General Electric

Raymond Fillion
General Electric

Katharine Gebbie*
NIST

Dan Gechtman
AXT

Kenneth Gertz
Rensselaer Polytechnic Institute

Mark Ginsberg*
Department of Energy

John Giuliani
Naval Research Laboratory

Lawrence Goldberg
National Science Foundation

David Goldston*
House Science Committee

Benjamin Greiner
Embassy of France

Chris Hayter
George Washington University

Roland Haitz
Agilent Technologies

Jonathan Hardis
National Institute of Standards and Technology

John Horrigan
Pew Internet Project

Richard Jarman
Eastman Kodak

Steve Johnson
Lawrence Berkeley National Laboratory

Zakya Kafaki
Naval Research Laboratory

*Speakers

Bob Karlicek*
GELcore

Sheila Kennedy
Kennedy and Violich Architecture
Fred Kittler
Velocity Capital Management

Steve Kramer
New Technology Week

Norman Kreisman
Department of Energy

Raymond Kwong
Universal Display Corporation

Leslie Levine
Fusion Lighting

Ron Lewis
Department of Energy

William Loveless
Federal Technology Report

Janice Mahon
Universal Display

Toni Marechaux
Department of Energy

Clark McFadden*
Dewey Ballantine

James Mink
National Science Foundation

Michael Moloney
National Research Council

Nadarajah Narendran
Rensselaer Polytechnic Institute

Tom O'Brien
Dupont

Yoshi Ohno
NIST

Ed Petrow
Department of Energy

Thomas Picraux
Sandia National Laboratories

Barry Press
Washington CORE

Manijeh Razeghi
Northwestern University

Al Romig*
Sandia National Laboratories

Michael Scholand
Arthur D. Little, Inc.

Fred Schubert
Boston University

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