Report

Solid-State Lighting Portfolio
Building Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

October 2009

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ACKNOWLEDGEMENTS

The Department of Energy acknowledges and thanks all the participants for their valuable input and guidance provided during the 2009 DOE SSL Manufacturing R&D Workshops. The Department also thanks all the direct contributors and especially the following individuals:

Fairfax, VA, April 21-22, 2009

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Robert Steele, Strategies Unlimited
Yuan-Sheng Tyan, Eastman Kodak Company
Barry Young, OLED Association
Next Generation Lighting Industry Alliance

Vancouver, WA, June 24-25, 2009

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William Feehery, DuPont OLEDs
Miguel Friedrich, NextechFAS
Pat Gardner, SEMI
Mike Hack, Universal Display Corp.
Robert Harrison, Osram Sylvania
Andy Hawryluk, Ultratech
Uwe Hoffmann, Applied Materials
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This report was prepared for the U.S. Department of Energy and the National Energy Technology Laboratory by Akoya under NETL Order Number: DE-NT0005282.

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1. INTRODUCTION

As SSL technology advances, new challenges emerge that require a fresh approach and a new focus on manufacturing issues. In FY09, DOE launched an SSL manufacturing R&D initiative with two primary goals: to enhance product consistency and quality and to accelerate cost reductions through manufacturing improvements. A third objective is to encourage domestic U.S.-based manufacturing of SSL products.

To develop a working roadmap for the new SSL manufacturing R&D initiative, DOE hosted two workshops where chip makers, fixture and component manufacturers, and others joined DOE in exploring issues related to materials, equipment, process control, and other factors that influence SSL product quality and cost. The purpose of this report is to document the discussions held in those workshops. Section 2 of this report covers the first workshop, held April 21–22, 2009, in Fairfax, Virginia, and Section 3 covers the second workshop, held June 24–25 in Vancouver, Washington. Each section is divided into plenary sessions, LED sessions, and OLED sessions.

The Fairfax workshop was attended by nearly 200 lighting technology leaders, who focused on identifying key barriers on the path to lower-cost, higher-quality SSL products and making recommendations as to what should be done, who should do it and when, and what DOE's role should be. Participants were also encouraged to submit white papers describing their views on how the goals would be achieved. Their insights and recommendations were used to draft a "strawman" manufacturing R&D roadmap for review at the second workshop.

At the Vancouver workshop, the "strawman" R&D roadmap was reviewed and discussed by well over 150 attendees. The feedback from the Vancouver workshop led to a published version of the roadmap (September 2009) that represents industry consensus on the expected evolution of SSL manufacturing, best practices, and opportunities for collaboration. This roadmap will be updated annually so that it can serve as a long-term tool to guide the development of SSL manufacturing R&D, with an eye to accelerating market introduction of SSL for maximum national energy savings. The hope is that, by identifying key goals, target metrics, and a timeline, it will provide a common industry focus, reduce risk, and foster cooperation where appropriate.

The SSL Manufacturing R&D Roadmap also serves as an extension of the DOE SSL R&D Multiyear Program Plan, which for years has guided DOE efforts to accelerate the development and market introduction of high efficiency, high performance SSL products. It will inform and guide planning for the DOE SSL manufacturing R&D initiative, including solicitations for manufacturing R&D projects. A PDF copy of the roadmap is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-manufacturing-roadmap_09-09.pdf.

2. FAIRFAX WORKSHOP

2.1 Plenary Sessions

Plenary sessions at the Fairfax workshop covered such overarching topics as the worldwide supply chain, contract manufacturing, and an investor's perspective on solid-state lighting.

2.1.1 Welcome

James Brodrick, U.S. Department of Energy

Brodrick welcomed nearly 200 participants to the first-ever DOE SSL Manufacturing R&D Workshop by providing a broad overview of DOE's national strategy to accelerate SSL technology advances and successful market introduction of high efficiency, high quality, cost effective SSL products. He highlighted key DOE partnerships that strengthen the SSL program: a partnership with the Next Generation Lighting Industry Alliance (NGLIA), to enhance both manufacturing and the commercialization focus; a partnership with the Illuminating Engineering Society of North America (IES), to collaborate on strong lighting standards; and a partnership with the International Association of Lighting Designers (IALD), to improve lighting quality and energy efficiency.

Brodrick reviewed congressional appropriations for SSL from 2003 through 2009 and gave a proportional breakdown of where the R&D money is allocated between industry, academia, national laboratories, and small businesses. He also highlighted various DOE funding mechanisms that can be used to advance SSL R&D:

- Basic Research, which precedes the mission of DOE's SSL R&D program
- Core Technology and Product Development, which advances state-of-the-art SSL technologies for general illumination purposes
- Manufacturing Support, which achieves cost reduction of SSL for general illumination through improvements in manufacturing, while maintaining or enhancing performance
- Small Business Innovation Research (SBIR), which seeks to increase participation of small businesses in federal R&D.

Brodrick then offered an overview of DOE's market-based programs, including CALiPER testing of commercially available products; GATEWAY demonstrations of products in residential and commercial applications; the Quality Advocates initiative, which includes the consumer-friendly Lighting Facts label; the *L Prize* competition to develop two key lamp replacements (60W incandescent and PAR-38 halogen); the *Next Generation Luminaires* competition, which recognizes the best designed energy-efficient commercial luminaires; and the *Lighting for Tomorrow* competition, which recognizes the best designed energy-efficient residential luminaires.

2.1.2 Workshop Overview

Fred Welsh, Radcliffe Advisors

Welsh provided a quick overview of the workshop's objectives and overall process. He underscored the progress made with SSL to date, including rapid improvement in packaged device output and efficacy, but noted that future progress may be slower as limits are approached.

Welsh identified the key problem areas for SSL manufacturing as being high cost, inconsistent color, low light output, early failures, and over-promising performance. He explained that Day 1 of the workshop would focus on gaining a better understanding of which issues underlie these problems, and that Day 2 would be devoted to making recommendations based on those issues. Those recommendations would be used to develop a strawman roadmap to be refined at a follow-up workshop in June.

2.1.3 Worldwide Supply Chain for High-Brightness LEDs and Solid-State Lighting

Robert Steele, Strategies Unlimited

Keynote speaker Robert Steele (left) and DOE Program Manager Jim Brodrick (right)

Steele's keynote talk emphasized the global nature of the high-brightness LED supply chain. He noted that the six-fold market growth of the past ten years has been driven by applications other than lighting, and observed that the market is worldwide in scope, with the main production and consumption being centered in the U.S., Europe, Japan, Taiwan, South Korea, China, and Southeast Asia. He traced the evolution of white LED luminous efficacy in the best commercial products since 2000; gave a brief review of the vertical supply chain from substrate, to epitaxial wafer, to device, to packaged device, to system; and outlined the main production steps.

Steele then examined the structure of the high-brightness LED industry and presented a detailed analysis of the vertical supply chain. He noted the varying degrees of vertical integration among supplier companies, observing that this vertical integration is highly regional. He said that, as a general rule of thumb, epitaxy and wafer processing are worldwide, while packaging is currently done primarily in Asia. Steele took a close look at manufacturing in Asia, noting among other things that the largest growth in epitaxy and chip processing has been in Taiwan, South Korea, and China, and that while most production involves low-to-mid-range products, an increasing amount involves higher-performance products.

After identifying the major industry participants in high-brightness LED packaging, as well as the epitaxial wafer and chip suppliers, Steele examined the other elements of the LED supply chain, including substrates, reactors, process gases, phosphors, and encapsulants. He then turned his attention to LED lighting fixtures and their elements, and took a close look at the LED lighting fixture industry.

Steele noted that more than 400 companies are manufacturing SSL fixtures worldwide, with many of the smaller ones dedicated to SSL. In Europe, large lighting companies have begun significant LED luminaire programs, while in the U.S. the leaders have mostly been smaller companies, although larger companies have recently begun to show interest. Many companies in China are manufacturing SSL fixtures, and activity in Japan has picked up recently, but it still lags behind the U.S. and Europe.

After examining the structure of the LED lighting industry, Steele looked at its vertical integration, noting that the vast majority of LED lighting fixture companies are not vertically integrated, and that most never will be, because vertical integration is not necessary for them.

Steele reviewed the six largest suppliers for lighting applications to North American LED lighting manufacturers, and then looked at other components of the SSL fixture supply chain, including power conversion, thermal materials and heatsinks, and optical elements, before examining the issue of international patents, which he noted continues to be a contentious area. Steele concluded by observing that for the LED industry, "It's a double challenge: You can't just say I'm going to make this device 10 percent cheaper every year; you also have to bring the performance up."

2.1.4 Vision, Innovation, Reality: OLED Lighting – Completing the SSL Portfolio

Mike Hack, Universal Display Corporation

Noting the "tremendous improvements" in OLED efficacy over the past few years, Hack talked about OLED lighting as the missing element to complete the SSL portfolio. He observed that OLEDs and LEDs are complementary technologies that will each eventually find their own place in the market, with LEDs being used for high-brightness applications and OLEDs for large-area diffuse lighting. Hack explained that this is because an LED is a point-source high-intensity lamp, while an OLED is a large-area, thin, diffuse light source that's both transparent and flexible, and extremely sturdy and robust. He illustrated this latter point by showing a video clip of an OLED being repeatedly struck by a hammer without any apparent ill effects. Because of these unique advantages of OLEDs, Hack said, "their strength will be in new form factors."

Thin, transparent, flexible OLED forms

Hack next considered OLED opportunities for luminaire manufacturers, emphasizing the many advantages of OLED technology. In addition to their energy efficiency and suitability for novel forms and shapes, OLED fixtures will be cheaper than other fixtures because they're thin and use fewer materials. For the same reason, OLED fixtures will be lighter in weight and thus cheaper to transport. Hack also pointed out that OLED panels contain no hazardous materials, and that the diffuse lower luminance OLED source offers better visual appeal and comfort.

After examining the difference between OLED display and lighting applications, Hack reviewed the status of technical progress toward OLED lighting targets. He noted the lack of commercial OLED lighting products on the market today, identifying cost as the biggest barrier, and cited outcoupling as a key route to higher efficiency and longer lifetimes.

Hack then examined OLED manufacturing options and equipment needs, comparing the advantages and disadvantages of wet versus dry printing. After touching on the availability of critical materials such as iridium and indium, he identified major cost challenges. The major cost driver is the equipment costs rather than the organic costs, because of the vacuum deposition process. "Lowering the equipment costs is a key driver for the industry," he said, adding that "Already, OLEDs can be profitable a lot quicker than people think."

In examining routes to U.S. OLED manufacturing, Hack made the point that the U.S. has considerable expertise with OLED infrastructure but doesn't have any OLED panel manufacturers, and observed that Europe and Asia are investing heavily in OLED manufacturing. In conclusion, he emphasized that OLEDs offer energy-saving lighting products for which there is a clear market-driven need, that OLED technology has made tremendous progress, that lighting companies want OLED products, that the U.S. has considerable OLED expertise and infrastructure, and that costs are competitive.

2.1.5 Investor's Perspective on SSL Manufacturing

John Dexheimer, First Analysis Private Equity

Dexheimer explored today's investment trends and their implications for SSL. He pointed out that artificial lighting consumes 8 percent of energy and 22 percent of electricity in the U.S., for an annual cost of $50 to $70 billion. Dexheimer noted that "green investments" are not niche markets anymore – they have become more mainstream in their appeal, accounting for nearly 25 percent of venture capital in 2008. But when it comes to green investments, U.S. venture capital has focused mainly on solar energy.

To emphasize the point that green technology is a promising investment sector, Dexheimer cited a September 2008 survey that concluded that despite the present economic problems, venture capital investment will be driven significantly by the green technology sector, which will become the top investment sector by 2012.

Dexheimer examined the barriers to investment in SSL, noting that as a product business with recurring revenue, SSL is small compared to other green markets, and that its impact reduces a large portion of the incumbent companies' revenue and profits. But he stressed that there are good investment opportunities in different niches of the SSL supply chain, as well as in product entry with innovation, and that large-scale disintermediation of supply and distribution would bring a significant payoff.

Dexheimer stated that there are "pockets of opportunities" for venture capitalists in SSL. He noted that the total market for high-brightness LED driver integrated circuits is forecast to grow to more than $1.9 billion in 2011, which will register a combined compound annual growth rate of 38 percent. Further, wide-bandgap semiconductors/ materials are forecast to grow 30 percent or more per year through 2012.

He pointed out that those looking to make a profit might consider the long life of LEDs to be a liability rather than an asset, and he urged those involved in manufacturing to "think outside the box" about the structure of the SSL industry in order to come up with ways to address that and other hurdles, such as the high initial cost. He said that SSL companies should think of new business models and consider new partners to restructure costs and create distribution penetration.

Among the various models suggested were upstream integration, related product integration, full service offering via sales/marketing/service breadth, integrated service-financing-transactions model, novel markets, novel offerings not addressed, and partnering with incumbents or others. Dexheimer concluded that lots of capital has gone into the SSL sector with more coming, and that the lighting industry is ripe for substantial restructuring.

2.1.6 Contract Manufacturing for SSL

Robert Harmon, Jabil Circuit, Inc.

Harmon began by reviewing the advantages of outsourcing. One such advantage, he said, is avoiding investments in fixed assets, because electronic manufacturing services (EMS) providers have their own factories and generic production equipment. Another advantage is the ability to rapidly scale globally, making use of a skilled overseas work force. Harmon pointed out that outsourcing not only lowers labor costs, but also brings higher asset utilization, allows leveraged material spend, and entails less working capital. Outsourcing also allows companies to leverage additional EMS capabilities, adding bandwidth in design and product development, global logistics, and repair and aftermarket services. Harmon also noted that outsourcing enables companies to focus on their core competencies. "The most important thing is that it allows companies to focus on what they're really good at," he said.

Harmon stated that SSL has good synergy with EMS, because the relevant assembly processes are used in high volume for electronics manufacturing, and EMS factories and supporting supply chains are ideal for SSL products. He stated that EMS offers SSL the opportunity to avoid investments in fixed assets, achieve scale quickly, leverage the EMS supply chain and global footprint to reduce cost, and leverage EMS design capabilities. A globally integrated supply chain allows fast decision making, tight inventory control, added purchasing power, access to all manufacturing data, and consistent equipment processes and culture.

Harmon noted that not all SSL manufacturing has to be done overseas; when products are produced in high volume by automation or are very complex and require a high skill level to produce, it makes sense to build them in high-cost regions like the U.S.

2.2 LED Track

The LED track at the Fairfax workshop included detailed presentations on such topics as substrates, the economics of LED lighting, and LED phosphor manufacturing issues.

2.2.1 Driving Solid-State Lighting Through Manufacturing Cost Reduction: The Components of Supply Chain Excellence

Stanley Myers, SEMI

Myers discussed how the experience of the semiconductor industry in achieving long-term, significant cost reduction can be applied to cost reduction efforts for high-brightness LEDs. He began with a brief overview of SEMI, which is the industry association for the semiconductor and microelectronics supply chain, and the principal manufacturing standards development organization for semiconductor, display, and photovoltaic technologies. He then reviewed the progress to date in LED cost reduction though efficiency and drive current enhancements — as well as the increasing need for manufacturing efficiencies and yield improvements to contribute future cost reductions.

Today’s price of more than $25 per kilolumen for LEDs is more than an order of magnitude greater than DOE’s goal, Myers observed, adding that “breakthrough advances in a number of areas” are needed to reach that goal. He noted that merely doubling the efficiency of LEDs won’t be enough, and that “the remaining 8-10X cost reduction will come from yield improvements, productivity gains and manufacturing cost reduction.”

Myers underscored the striking degree of similarity between the high-brightness LED industry today and semiconductor manufacturing in the mid-1970s. He sounded an encouraging note by observing that since 1975, manufacturing efficiencies have reduced semiconductor cost by a factor of 500. He attributed this drastic reduction in significant part to the development of manufacturing standards, and cited a number of studies that have shown the value of standardization to industrial growth. One of those studies, conducted by the German Institute for Standardization, concluded that standards contribute more to economic growth than patents and licenses. “The purpose of these standards is to drive down cost,” he said.

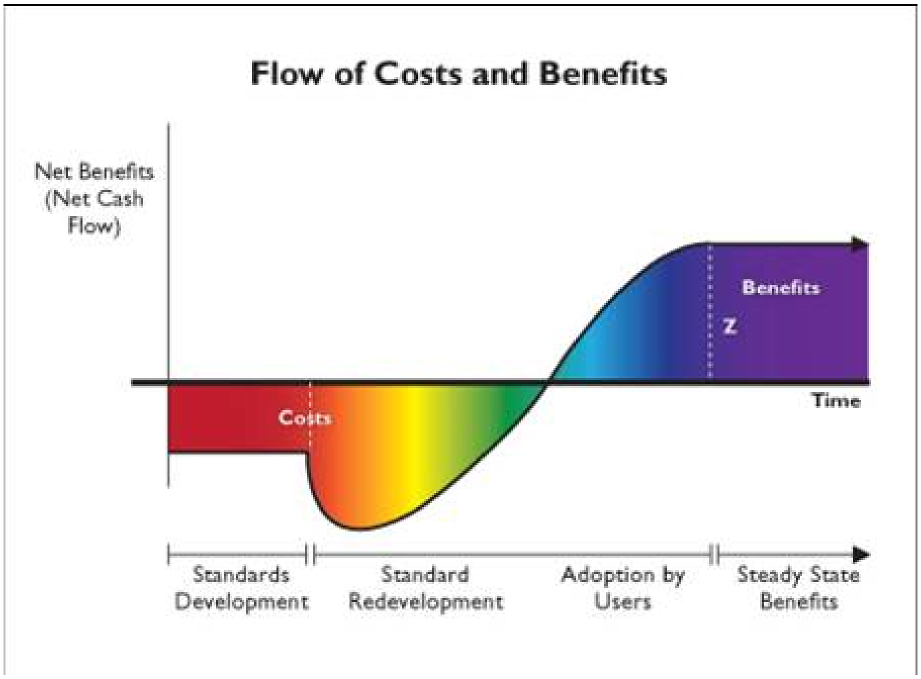


Figure 1. Manufacturing standards: flow of costs and benefits

Myers expressed his conviction that the same manufacturing efficiencies that reduced semiconductor cost over the past three decades will enable high-brightness LEDs to penetrate the general purpose lighting market, and that industry collaboration — facilitated by standardization — is an important key. “We believe that effective industry collaboration is the best way to reach the 10X manufacturing cost reduction goal necessary for the rapid penetration of high-brightness LEDS into the broad-based lighting and illumination markets — which are both massive business opportunities *and* critical energy efficiency targets vital for the planet,” he said.

Myers concluded by proposing the establishment of a high-brightness LED manufacturing forum, where leading LED manufacturers can work in conjunction with suppliers to identify and develop critical industry standards, so that all involved “can focus on what really counts — innovation and creativity.”

2.2.2 LED Manufacturing: Technologies and Costs

Jeff Perkins, Yole Développement

Perkins took a close look at the technologies and costs involved in LED manufacturing, identifying key metrics and players, detailing the main steps of the LED manufacturing process, and breaking down the different elements of the production costs. He began by noting that the LED market was about $5.1 billion in 2008, with a volume of more than 50 billion units, and that LED applications are currently dominated by portable device backlighting (mobile phones, PDA, GPS). He observed that higher-brightness LEDs have begun to address other promising markets, such as automotive, LCD backlight, and general lighting. At present, low-end LED products account for 83 percent of the market, high-brightness LEDs 15 percent, and emerging ultra-high-brightness products 2 percent.

Perkins emphasized that higher efficacy is needed for the general lighting market, pointing out that overall efficiencies of around 73 percent can be achieved for low-current LED operation (generally 20mA) but that for high-power LEDs (350mA) driven at high currents, overall efficiency drops to 25 percent. Perkins noted that 10 key technologies to increase LED efficiency are now in use or under investigation.

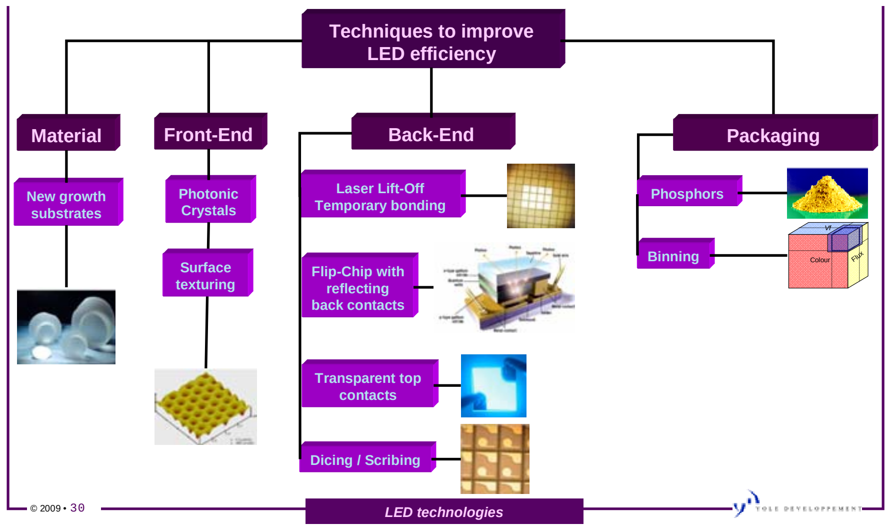


Figure 2. Various techniques to improve white LED efficiency

Perkins presented an analysis of production costs for packaged LEDs and identified a number of techniques to improve LED efficiency and costs, starting with new and improved materials and front-end improvements in photonic crystals and surface texturing. On the back end, he discussed laser lift-off techniques, LED scribing and dicing, and packaging issues related to phosphors and binning. He concluded by noting that work is being done at every stage of LED manufacturing to increase efficiency, and corresponding cost trade-offs occur at each stage.

2.2.3 LED Device Manufacturing Issues

Mike Krames, Philips Lumileds

Krames focused on what can be done in the near term to reduce LED device manufacturing costs. Calling a 20-fold improvement in the near term “absolutely doable,” he discussed metalorganic chemical vapor deposition (MOCVD) epitaxy as the path to low-cost manufacturing. He noted that “the choice of the substrate early on in the process has dramatic effects downstream,” and that “GaN substrates are much too expensive today.”

Krames identified thinning and dicing, along with advanced lithography for large, bowed wafers, as critical front-end issues that need to be addressed. On the back end, he said, critical issues include packaging materials (optical, interconnect, and submount technologies), improved techniques for high-speed die inspection, and increased accuracy and scope of color testing.

With regard to LED packaging, Krames noted that power handling capability increased more than 100-fold over the last ten years. He made the point that it's much more difficult to engineer a system to keep a constant color range than to keep a constant lumen range — a problem that is compounded by the fact that "the eye is more sensitive to color change than to lumen change." And he identified cost, lifetime, efficiency, and color quality as key limitations to mass adoption of LEDs.

2.2.4 LED Luminaire Manufacturing Issues

Paul Pickard, Cree LED Lighting Solutions

Pickard began by examining what drives the costs of LED luminaires, citing market requirements for lifetime, lumen output, efficacy, and electrical specifications as well as regulatory/standard requirements (UL, FCC, ENERGY STAR®, and ANSI) and macroeconomics. He discussed the current lack of clarity as to which standards apply, and how one applies standards from other products, questioning whether power factor matters, whether dimming is a requirement, and whether current form factors are relevant.

As an example of a present constraint, Pickard cited form factors, noting that fitting into existing shapes (such as ANSI bulb standards) constrains the overall performance and cost of LEDs. He also cited performance expectations, focusing on dimming and the power factor. Pickard raised the questions of whether it's too early in the technological cycle to standardize, whether standardization will compromise performance, and whether standardization will reduce cost. He said that the industry should avoid premature standardization and should not skimp on building quality products, but should strive toward smart system-level designs that scale in volume and across platforms.

To reduce overall system cost, Pickard advocated driving down the cost of the LED component (chip and packaging) as this is a major contributor to luminaire costs, and noted the need to eliminate "droop" in the LED and strive for greater LED consistency. In addition, he called for more consistency in the power supply and raised the question of whether we're setting the standards for LEDs too high for things like dimming and power factor, compared to the CFL technology that LEDs must displace. Finally, Pickard advocated designing LED manufacturing for automation in order to achieve consistency and meet high-volume demand.

2.2.5 Substrate Matters

Keith Evans, Kyma Technologies, Inc.

Evans began by noting that native substrates are preferred, and that when cost-effective native substrates are not available, "difficult choices must be made." He stated that comparing substrate approaches is difficult, because everything varies with the substrate — including size availability, surge capacity, surface finish specifications, substrate cost,

cost of epitaxy, thermal expansion match, lattice match, thermal conductivity, epiwafer defect structure and thermal impedance, device properties, intellectual property issues, compatibility with existing equipment and processes, and need or desire to remove in backend processing.

Evans reviewed the GaN LED substrates that are used today, including sapphire, which is very inexpensive; patterned sapphire, which gives improved IQE and extraction efficiency; and silicon carbide, which is a good thermal conductor. After examining the issue of wafer diameter, he raised the question of whether bulk GaN will ever be cost-effective and then discussed templates, epitaxy throughput, and newer substrates.

He predicted that “the continuing drive to begin epitaxy with an epi-ready GaN surface and to enjoy improved device layer structural quality in a faster epitaxial growth process will drive the substrate trend from foreign substrates to templates and onto native GaN, perhaps going further to something more exotic.”

Among the primary challenges Evans identified was making templates that are cheap yet of high structural quality, without serious bow issues — which he said would require advanced multi-wafer processing equipment. He also cited the need to make native GaN cheap and large and high quality, preferably with a nonpolar or semipolar orientation.

In conclusion, Evans emphasized that substrate matters impact both cost and performance of LEDs, and predicted that the forward trend with substrates will be towards native GaN, although templates and other approaches may be intermediate solutions. He noted that vertical cooperation within the supply chain could accelerate progress.

2.2.6 Epiwafer Equipment and Processing

Sudhakar Raman, Veeco Instruments, Inc.

Raman began by reviewing the LED market landscape and reiterating the basic market challenge of overcoming the low cost of incandescent lamps and the high efficiency of CFLs. In discussing blue LED application drivers and challenges, he stated that lighting and display are the biggest growth drivers moving forward, and that MOCVD evolution of yield and wafer size will enable growth.

Raman observed that improvements in epi performance have multiplying effects in the overall cost reduction for LEDs. “Fundamentally, everything starts on the front end,” he said. “The source of the problem is in the front. As the epi performance process goes up, the chip price goes down.”

In discussing LED uniformity and repeatability issues, Raman identified three focus areas to increase yield and lower cost per wafer: improve binning through uniformity improvements, increase productivity to reduce cost of ownership, and reduce source consumption. In-situ monitoring and control of wafer temperature and wafer curvature (deflectometers) will be required to meet future wavelength uniformity and reproducibility targets.

In conclusion, Raman noted that significant technology challenges remain in order to increase yield, and predicted that improvements will be achieved through epitaxial growth process, process control (use of in-situ monitoring), and epitaxial equipment, and that wafer size changes will continue to challenge existing technology to improve uniformity and yield. A new generation of epitaxial deposition equipment will be needed to address the cost-reduction goals of SSL.

2.2.7 LED Phosphor Manufacturing Issues

Anant Setlur, GE Global Research

Setlur began with an overview of current LED phosphor technology, and noted that this is a heavily patented area. He then turned his attention to the major phosphor suppliers, noting that the largest LED manufacturers have in-house phosphor manufacturing capability as well as phosphor R&D resources, and/or supply agreements with small-scale phosphor manufacturers. He made the point that each manufacturer likely has its own specific process and compositions for the same base material, leading to unique performance (color, absorption, efficiency, thermal quenching, etc.).

In reviewing current LED phosphor manufacturing, Setlur focused on Ce^{3+}-doped garnets and Eu^{2+}-doped silicates, sulfides and selenides, nitrides, and emerging LED phosphors such as Mn^{4+}-doped fluorides. He then turned his attention to general cost issues, noting that low LED phosphor volume prevents automation and incurs high labor costs, that high-purity raw materials and rare earth content (e.g., Eu) add significant cost, that intellectual property (IP) value (license fees or royalties) may also be included in pricing by suppliers, and that advanced phosphor synthesis techniques (e.g., ceramic/ incorporation in glass) balance additional cost versus reduced waste and potential performance.

In conclusion, Setlur observed that as the LED phosphor field is starting to mature, supporting industries are starting to target LED phosphor applications, and that there are many players filing for international patents on phosphor composition and use in LEDs. Current LED phosphor manufacturing costs are high due to low volumes and/or difficult manufacturing processes, and inherent efficacy gaps exist for current warm white/high CRI LEDs requiring new phosphor development.

2.2.8 Economics of LED Lighting

Eric Haugaard, BetaLED

Haugaard compared the economics of LED lighting and HID lighting, focusing on the specific question of whether LED product solutions have the potential to more positively impact the environment and the economy than HID-based solutions because of lower associated energy, waste, maintenance, and disposal costs. The possibilities he considered included lower total encompassed energy cost to produce the LED product alternative, lower product life cycle costs (including lower total encompassed energy cost to maintain and dispose of the LED product alternative, and lower operating energy over life), lower first cost/first installed cost, greater recyclability (due to higher recyclable content as well as lower net cost and energy required to recycle), and higher U.S.-based manufacturing content.

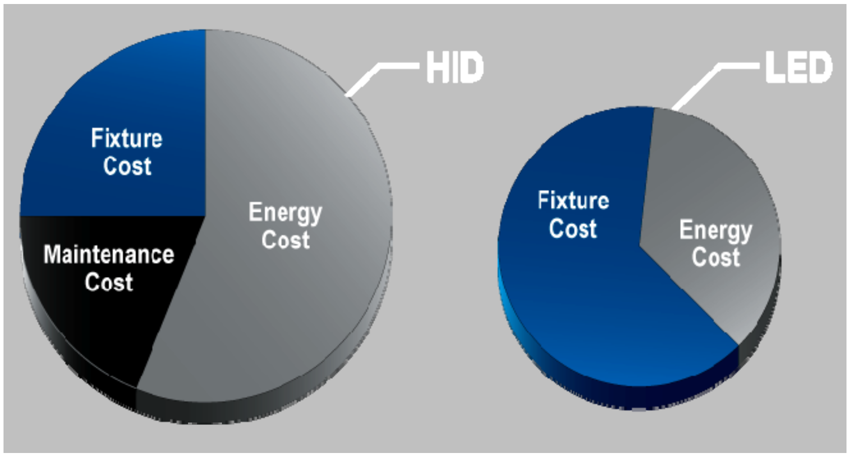


Figure 3. Value analysis: total cost of ownership

Haugaard compared the product life cycle material processing and handling of LED and HID technologies, as well as the typical manufactured components, and he also addressed the question of mercury content in metal halide lamps. In addition, he addressed the economic challenge of cost scaling for LED products.

Haugaard cited lower manufacturing process energy consumption for comparable lighting performance, lower transportation resources required, and a smaller carbon footprint as possible current and future benefits of LED over HID. He identified as possible barriers to LED adoption high first cost, long payback period, product warranty shortfall, uncertainty in predicted long-term performance, lumen maintenance, color stability, insufficient or incomplete product performance and reporting standards, and lack of application-level experience and recommended practices.

2.3 OLED Track

The OLED track at the Fairfax workshop included detailed presentations and panel discussions on such topics as critical materials, roll-to-roll solution processing, and OLED architecture.

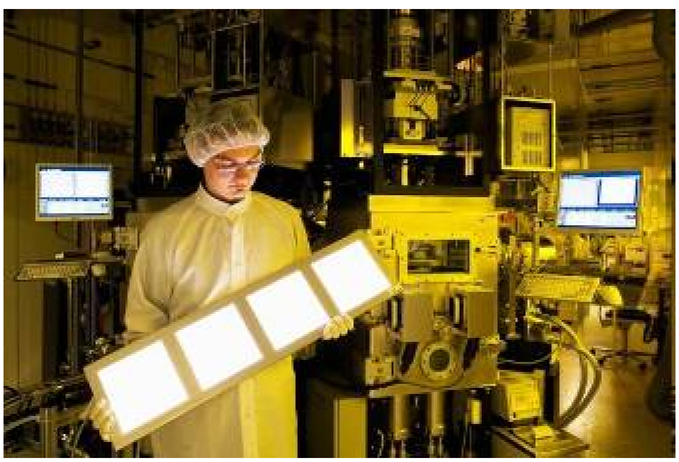
2.3.1 OLED Manufacturing

Barry Young, OLED Association

Young began his presentation by describing the OLED Association, which consists of display and lighting manufacturers. He then described the history of passive matrix (PM) OLED display manufacturing, because PM displays are similar to the type of panel that would be used for OLED lighting. Young stated his belief that the future of the OLED display business is in the production of active-matrix displays. However, these displays are currently twice the price of LCDs of the same size. Still, demand is on the rise. Participants in this market include TM Display, which is expected to have product this year, TPO, Panasonic, and Canon. In 2008, 7 million active matrix displays were sold for $220 million. This market is also being driven by Samsung, which is doubling its capacity by the end of 2009, when it will be producing about 1 million displays a month.

Young then summarized manufacturing techniques for OLED displays and stated the costs of various substrates for OLEDs. Challenges in this area are backplane scaling, deposition and patterning scaling, blue material efficacy and lifetime. OLED cost models developed by Young confirmed that substantial cost reductions must be achieved for lighting applications. Specific cost challenges include reducing the waste of organic material from 90 to 20 percent, reducing substrate cost from $20/sq. m to <$3/sq. m, and reducing encapsulation/electronics costs by 67 percent.

He cautioned that OLED lighting systems should be compared with other luminaires, not other individual lamps, and compared LED systems with OLEDs by showing CALiPER results for LEDs. He pointed out that some manufacturers do not give warranties for the entire rated lives of LED products, and recommended looking at LED lifetime in terms of warranties. He asked, “What is lifetime if the manufacturer isn’t guaranteeing it?” and noted the range of warranties available on LEDs from 3 years, to 12 months, to 60 days. Finally, he described manufacturing challenges for OLED lighting in the areas of luminaire cost, efficacy, and lifetime, as well as the usage of different metrics (such as T_{70} for lifetime).



Large Area OLED lighting panel (80x20 cm²) by Fraunhofer IPMS

2.3.2 OLED Lighting Manufacturing Cost

William Feehery, DuPont OLEDs

Feehery opened his talk by asking “why OLED for lighting?” To date, DuPont’s focus has been on OLED display manufacturing through solution printing, but the company predicts that OLED technology will also be successful in general lighting applications using this method.

As the company does for other products, DuPont began with cost targets and worked backwards to see where they'd need to be to compete. With this in mind, Feehery gave an overview of challenges and possibilities for OLED lighting and described a reasonable price target for OLEDs of 80 lm/W efficacy given today's manufacturing technologies and a 90 percent yield. He stated that 5 years would be the required OLED lifetime to break even with 2- by 2-foot fluorescent troffers, or about a 40,000 hour lifetime. He declared that the usage of longer-lifetime materials at a higher luminance can help to reduce costs, and emphasized the need to choose a manufacturable structure and developing technology to enable it.

Feehery then described cost issues for OLEDs in further detail by touching upon substrate choice, photolithography, and equipment investment cost per layer. He reviewed several manufacturing processes currently available for OLED lighting, including evaporation using a point source or a linear source, coating or printing. He noted that longer lifetime materials would enable increased luminance, reduce the area, and therefore reduce cost.

When examining where OLED lighting is today, Feehery noted that currently available OLED light panels are far from the price and performance targets he mentioned. He added that OLED lighting will be the future, if we solve the right problems today: finding a low-cost substrate to overcome the high cost of display glass; lowering encapsulation costs; reducing substantial capital investment required with each layer by achieving high efficiency with a minimal number of layers; using solution coating of layers wisely; and finding long lifetime materials to drive brightness up while driving costs down. In closing, he offered additional recommendations for a manufacturing roadmap: scale up (size and volume), and reduce material cost and waste.

2.3.3 OLED Architecture — Implications for Manufacturing

Yuan-Sheng Tyan, Kodak

Yuan-Sheng Tyan began his talk echoing previous speakers' statements that OLED lighting should be compared to other luminaires, not lamps. He showed efficacies of competing technologies and stated that on a luminaire comparison basis, OLEDs have already demonstrated competitive efficacy. Then he shared several keys to high performance: creating multi-layer structures with tandem architectures, internal extraction enhancement, and hybrid architectures using fluorescent blue with phosphorescent green and red. He showed how a tandem architecture provides twice the OLED in the same area, and reduces area-related materials and processing costs.

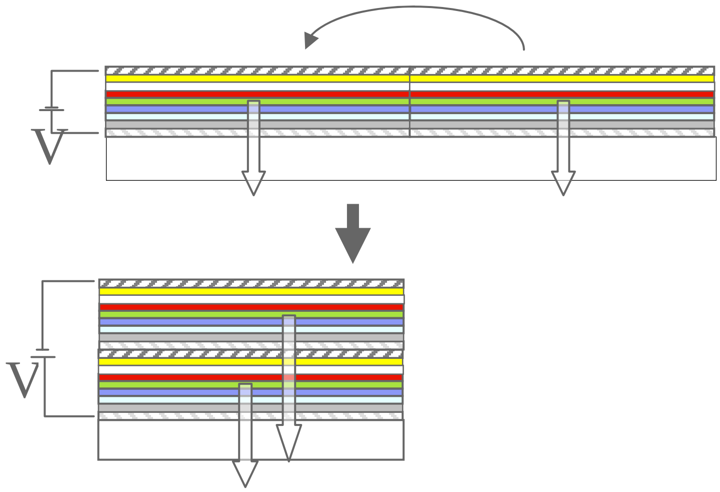


Figure 4. Tandem OLED architecture

Tyan reviewed manufacturing processes and stated that the vacuum deposition process used for OLED displays is too expensive, and that new technology is needed to improve processes. To address this, Kodak developed the Vapor Injection Source Technology (VIST) manufacturing process. He shared a cost estimate for an OLED lighting tile made with this process, showing that the VIST process has demonstrated it supports low-cost fabrication of complicated layer structures needed for high performance. He also noted that vacuum-evaporated OLED devices have demonstrated ENERGY STAR® color and performance levels of 65 lm/W, with a CRI of 86. He highlighted that 50 lm/W is better than 95 percent of commercially available downlight luminaires.

In addition, Tyan pointed out that an OLED panel is "almost" a luminaire, and that fixture loss is minimal. He then described challenges facing OLED developers, such as the need for light extraction enhancement structure, understanding the mechanisms that produce IR loss, and what causes shorting defects. He acknowledged that other issues must be addressed to produce OLEDs with long shelf lives, such as susceptibility to moisture, and noted that the shelf-life requirement may necessitate the use of glass or metal substrate encapsulation. He closed by noting that improved barrier methods were also needed.

2.3.4 Mainstreaming OLEDs for the Future of OLED Lighting

Peter Ngai, Acuity Brands Lighting

Ngai described the hope that OLEDs will "reinvent lighting" in various sectors of the lighting industry. He stated that because OLEDs are useful for diffused lighting, and LEDs are useful for focused light, the two technologies do not necessarily have to compete. Because of OLED characteristics, the technology will compel architects and designers to rethink their approaches to lighting designs, and this new lighting design platform will allow a whole new level of integration of lighting and architecture that is not possible with current technologies.

Ngai reminded the group to compare OLEDs to traditional luminaires. He described the range of brightness levels and areas that OLEDs could have in order to replace traditional fluorescent ceiling luminaires. He discussed physical issues and features that he believed the OLED lighting industry should focus on, such as the production of physically resilient OLEDs with consistent color, dimming capabilities, and a T70 of at least 25,000 hours. He then presented a roadmap for the production of mainstream OLEDs, stating that such OLEDs need a minimum efficacy of 60 lm/W.

Finally, Ngai spoke about the lighting industry's vision for OLEDs. He described how most existing lighting systems are by and large unappealing. "When we look up at the ceiling, what do we see? Metal boxes, tin cans, aluminum tubes, baffles, louvers, plastics, lamps, sockets, pieces of disorganized brightness patches — visual clutter." He noted how they interrupt the architectural harmony of the space, and that designers even apologize for putting luminaires on the ceilings. He emphasized that lighting should do more than provide us with the basic ability to see, that the richness of colors and color dynamics offer potential aesthetic and emotional effects.

2.3.5 Deposition Equipment and Processes for OLED Lighting

Uwe Hoffmann, Applied Materials

Hoffmann began by reviewing three general steps involved with the production of OLED luminaires, and the advantages and disadvantages of different processes. The three steps start with the front of the line, where basic materials such as SiO2, TCO/ITO, and metal are deposited. Next, the OLED stack, or the core, is where surface treatment takes place, followed by deposition of the organic layers and metal for the upper electrode. The third step is the back end, where encapsulation takes place with either a glass or metal cap or thin film.

Hoffmann focused on the OLED stack step, delving into the keys to this process. He made the case that a "dry" vacuum process used with small molecule organics is more advantageous than a "wet" solution-based process used with polymers or small molecules in solution. He pointed out that greater performance, industry adoption, and expected price developments make the vacuum process a better choice.

Next, Hoffmann presented industrial evaporation source concepts, as evaporation is an important part of the process. Hoffmann weighed the benefits of point sources, area sources, and linear sources, and demonstrated the material utilization of the source concepts. Applied Materials chose the linear source method because it uses a relatively high material utilization, has a low thermal load, low cost of ownership, and is easily scalable. Point sources require a large distance between substrate and crucible to get good uniformity, and have a lower material utilization rate.

Next, Hoffmann discussed the coating step, and reviewed the concepts of cluster, horizontal inline, and vertical inline coating, As the company analyzed the source concept, it carefully considered coating concepts, determining that the cluster concept with the point source are the most advantageous for a Generation 2 device. However, greatly improved throughput and lower layer costs in a newer generation device mean that in-line with linear source coating is more appropriate for these applications. Hoffmann believed that a vertical deposition was more favorable than a horizontal deposition based on the lack of mask sagging and glass bending, and the lower particle contamination.

Based on these analyses, Applied Materials has developed a New Aristo vertical in-line system for white OLED fabrication. The system utilizes a continuous substrate flow and a vertical coating process, improving throughput and material utilization. The system does not bend the glass, it is easy to scale up and to maintain. In developing this system, Applied Materials tested three types of evaporation sources: organics, Lithium Fluoride/Silver and Aluminum. Hoffmann demonstrated that these evaporation techniques also have proven to have the shortest tact time, with no loss for handling, and can provide a homogenous coating for improved OLED device performance.

2.3.6 Roll-to-Roll Solution Processing

Anil Duggal, GE Global Research

Duggal began his presentation by offering comparisons between LEDs and OLEDs. He emphasized the constant expansion of LED capabilities, including recent LED product developments in diffuse lighting applications, such as backlights and televisions. He stated that this means that OLEDs can no longer rely on the ability to create diffuse light as a competitive advantage over LEDs. In order to compete with LEDs, OLED technology must now focus on cost reduction. This need led GE to commit to a roll-to-roll OLED fabrication method.

First output of early roll-to-roll line

Arriving at this decision required a detailed analysis of the cost structure of various OLED fabrication methods. Duggal's team examined the capital equipment costs associated with three types of manufacturing plants and determined that it was better to build a large scale plant with the ability to scale up at low-cost. According to Duggal, this is consistent with a roll-to-roll wet approach, whereas a "dry" approach would require much larger capital investments when trying to scale-up manufacturing capabilities.

The desire to minimize costs also led GE to partner with Energy Conversion Devices to prove that continuous roll-to-roll OLED fabrication is possible. Early runs from this process were successful, but resulted in a high number of malfunctions; and while the current output has advanced greatly, many issues must still be resolved.

Currently, the GE team is researching issues such as what wet-coating techniques will be used, what hermetic method should be used, and whether an all-wet process is the best approach. The team has discovered that post-process patterning is possible. They can remove organic layers from the OLED polymer coating without damaging underlying inorganic coatings on plastic web. The method utilizes a wiping head that harmlessly "cleanses" the OLED. Before the roll-to-roll product is brought to market, it is critical for GE to perform future development and detailed evaluation of low-cost process steps and their influence on device performance.

2.3.7 Critical Materials for OLED Lighting

J. Norman Bardsley, Bardsley Consulting

Bardsley's presentation focused on the materials used in the OLED lighting market. Bardsley stated that companies that currently have the highest margins in the OLED display market are the same companies that manufacture the critical materials used for production of OLED displays. He maintained that companies that invest in critical materials for OLED lighting would be well positioned, as the material market could be a $5 billion industry.

Bardsley discussed many of the critical materials used for OLEDs. Specifically, he reviewed materials used for the substrate (glass, foils, plastics), substrate coatings, encapsulation technologies (cover, seals and getters), electrodes (anode and cathode), luminescent materials, hosts and transport layers, out-coupling enhancement, electrical connections, and drive electronics.

For each of these materials, manufacturers must consider optical and electrical efficiency, light quality, lifetime, and manufacturing and operating cost. Bardsley explained that many existing materials do not satisfy an OLED's requirements for lighting. For example, Indium Tin Oxide (ITO), a transparent conducting oxide used as the anode for many OLEDs, is too expensive to manufacture. Current materials used for out-coupling enhancement also face many issues — some are too expensive, while others impact device operation, or change the color or angular distribution of the OLED. In some instances, the cost of processing is more critical than the cost of materials. Some materials are simply hard to come by, as in the case of iridium, one of the rarest natural elements. Although it is used in small quantities in the most popular phosphorescent emitters, the industry still seeks a true blue phosphorescent emitter with a long lifetime.

Bardsley also provided a European perspective of light extraction, and described issues with out-coupling structures and enhancement. He suggested that perhaps combining solutions might help overcome these barriers. Bardsley noted that both the cost of OLED materials and the quantity used in manufacturing for lighting need to be reduced. In addition, materials must perform better for lighting than they currently do in OLED displays. He noted that processing costs far outweigh the cost of raw materials, and suggested studying the interactions between the different layers. Bardsley urged material suppliers to work with equipment companies and device designers. In concluding the presentation, Bardsley reiterated the close connection between the OLED display market and OLEDs for lighting, stating that material producers that are successful in the OLED lighting market would also be successful in the OLED display market.

2.4 Fairfax Workshop Process

Every presentation and panel discussion at the Fairfax workshop was followed by an open discussion period, during which all the attendees had the opportunity to ask questions and make comments.

In addition to the presentations and panel discussions, a significant portion of the workshop was devoted to breakout sessions split into two groups, one for LEDs and one for OLEDs. The separate tracks reflected the fundamental differences between LEDs and OLEDs, including underlying technology, manufacturing processes, and the current stage of commercial development, with LED technology considerably more advanced.

The breakout sessions were devoted to open discussion rather than formal presentation. In them, attendees identified key barriers on the path to manufacturing lower-cost, higher-quality SSL products and made recommendations as to what should be done, who should do it, when they should do it, and what DOE’s role should be.

These insights and recommendations, supplemented by a number of white papers solicited at the workshop and submitted by participants afterwards, were used to draft a “strawman” SSL Manufacturing R&D Roadmap to be reviewed and discussed at the follow-up Vancouver workshop in June, with an eye toward refining and publishing it.

3. VANCOUVER WORKSHOP

3.1 Plenary Sessions

Plenary sessions at the Vancouver workshop covered such overarching topics as cooperation between manufacturers, U.S. manufacturing, and standards.

3.1.1 Welcome and Recap of the Fairfax Workshop

James Brodrick, DOE

DOE SSL Portfolio Manager James Brodrick kicked off the second manufacturing R&D workshop in Vancouver by emphasizing the urgency of the task at hand. “There’s not a moment to lose,” he told the audience, referring to the potential of SSL lighting to help curb the nation’s tremendous energy use, which has raised environmental and resource concerns.

Brodrick offered a recap of the Fairfax workshop, reiterating that high cost and inconsistent quality are key barriers to market acceptance of SSL. He noted that these issues call for a focused, national, industry-wide effort, emphasizing that collaboration is the key to success. He outlined DOE’s new SSL manufacturing R&D initiative, which has two primary goals: to enhance product consistency and quality and to accelerate cost reductions through manufacturing improvements. Another objective is to encourage U.S.-based SSL manufacturing. He noted that a panel session on U.S. manufacturing would follow later in the workshop, where industry experts would offer varied perspectives on the issues that impact manufacturing decisions.

Pointing out that the SSL Manufacturing R&D Roadmap will play a key role in guiding and informing the DOE manufacturing R&D initiative, Brodrick reviewed the timeline and approach for developing the roadmap, including the recommendations from the April workshop for both LEDs and OLEDs. He outlined DOE’s comprehensive program strategy to move SSL to market, which includes research, product development, manufacturing, standards development, and commercialization support.

3.1.2 Systems Approach to Manufacturing

Mark McClear, Cree, Inc.

McClear talked about the advantages of an integrated approach to manufacturing. He noted the complexity of SSL systems, and pointed out that lifetime, maintenance costs, energy savings, and design all have an impact on the value. He stated that performance quality improvements put constraints on cost improvements, noting that the biggest part of the cost improvement equation is LED performance gains, but any manufacturing cost optimizations should not decrease performance, quality, or reliability.

McClear suggested that taking a comprehensive, integrated system approach in the areas of LED chips, components, and luminaire thermal, optical, and electrical design could be a path to increasing quality and performance at low cost. “There isn’t one single magic bullet,” he said. “It’s going to be a lot of small fixes, but in an integrated way.”

He noted that LED materials, chip design, component design, luminaire thermal design, luminaire optical design, power supply circuit, and white light generation and quality are all important considerations, and that cost must be balanced with efficiency, reliability, quality, and customer expectation (Figure 5).

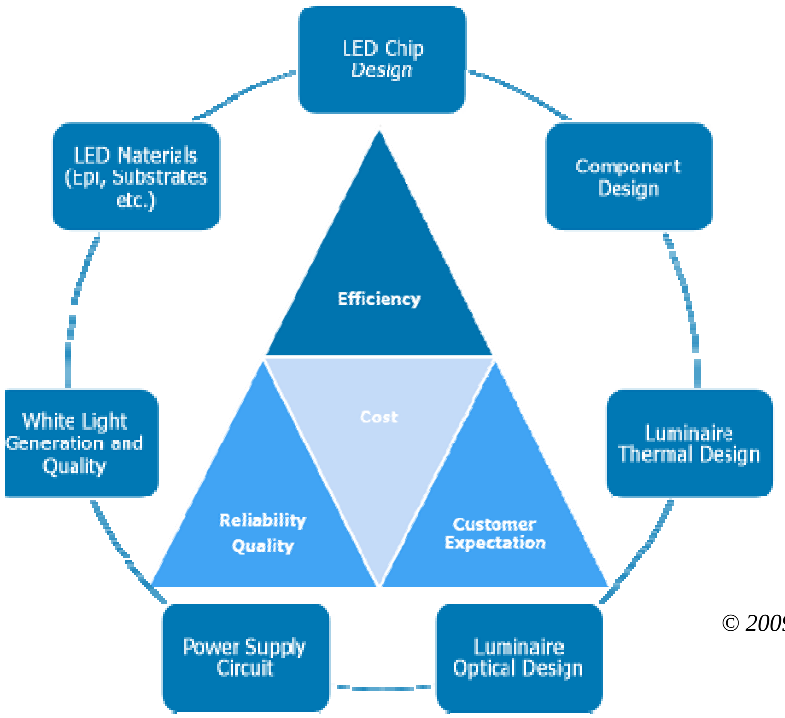


Figure 5. Integrated approach: no single magic bullet

As shown in Figure 5, McClear pointed out that the goal is to optimize the luminaire on two vectors — technology/manufacturing and performance/cost — and observed that technology developments have been successful by optimizing subsystems, but that subsystem optimization without regard to system integration may not deliver the expected cost reductions. Simplification of the SSL luminaire, he said, is essential to real cost reduction.

3.1.3 Competition and Cooperation: The SEMATECH Experience
Scott Kramer, SEMATECH

Kramer drew on SEMATECH’s experience to illustrate the principle of what he called “coopetition,” which occurs when competing companies cooperate to their mutual advantage, and which he believes is a key to advancing the SSL industry.

Kramer explained that SEMATECH is a consortium of the world’s leading semiconductor manufacturers as well as equipment and material suppliers, all working together on the industry's precompetitive challenges and infrastructure in order to accelerate technology innovation and manufacturing by bringing together the resources of many entities to solve problems and share cost and risk.

Kramer traced the history of SEMATECH, from its founding in 1987 to the present, and noted that the organization has changed drastically in response to changes in the industry. Initially funded by the U.S. government, it became funded by the chipmakers in the early 1990s and became international in 1996. "SEMATECH is a classic example of an organization that's totally reinvented itself," he said. "What you see as SEMATECH today is totally different from its ancestors."

Genesis	Feasibility	Product Development	Manufacturing
Eureka	*Eureka / Sweat*	*Sweat*	*Sweat*
Individual	*Small team*	*Large team*	*Large team*
$	*$$*	*$$$*	*$$$$*
Open IP	*Open IP*	*Closed IP*	*Closed IP*
Success is rare	*50% success*	*100% success*	*100% success*

Figure 6. Stages of innovation

Kramer outlined the stages of innovation — from genesis, to feasibility, to product development, to manufacturing — as well as the challenges of productivity, cost reduction, and sustainability. He discussed the International SEMATECH Manufacturing Initiative (ISMI), and the ISMI Environment Safety and Health (ESH) Technology Center, a comprehensive, worldwide, collaborative R&D center dedicated to cooperatively finding and implementing the most cost-effective, environmentally friendly manufacturing processes and procedures.

3.1.4 SSL Manufacturing R&D Roadmap

Fred Welsh, Radcliffe Advisors

Fred Welsh of Radcliffe Advisors introduced the SSL manufacturing R&D "strawman" roadmap, developed from feedback given in the April workshop. He went over the main roadblocks identified in the roadmap, breaking them down by category.

LED luminaire roadblocks included variability and the need to bin the LEDs, uncertain long-term performance, high cost of product testing, and lack of industry-wide design software, as well as the fact that power supplies/drivers are expensive and hard to specify.

Roadblocks for packaged LEDs included substrate issues (such as the warping and defects in the present materials, and the fact that potential alternatives are costly or unproven), epitaxy issues (such as wavelength non-uniformity and variations in chip output power), a lack of suitable manufacturing equipment, and the fact that process controls are not adequate.

OLED roadblocks included a high level of risk, which deters needed capital investment; the need for volume to achieve cost goals; and the absence of OLED "foundation materials" such as substrates, moisture barriers, planarization or insulation layers, transparent conductors, and extraction enhancement layers.

Welsh urged attendees at the Vancouver workshop to recommend changes to the draft roadmap, define steps needed to implement the roadmap, define steps for DOE to take, and recommend ways to encourage U.S.-based manufacturing. "Let's get an understanding of what needs to be done," he said.

Welsh also discussed SSL standardization issues, including the lack of uniform reporting of luminaire performance, the fact that light sources are not easily replaceable, and the need for standardized luminaire components (such as LEDs, drivers, and optics). He noted that a panel session devoted to this topic would follow later in the workshop, offering varied perspectives and updates from industry experts. In conclusion, he emphasized the roadmap goals:

- Achieve consensus on the expected evolution of SSL manufacturing to guide equipment and material suppliers
- Identify ways to reduce risk and reduce costs
- Identify best practices to reduce product variability and increase yields
- Identify needed manufacturing standards work.

3.1.5 Panel: U.S. Manufacturing in a Global Lighting Industry

James Brodrick, DOE (Moderator); Keith Cook, Philips Lighting; Robert Harrison, Osram Sylvania; Heng Liu, Bridgelux; Govi Rao, Lighting Science Group; Kevin Willmorth, Lumenique

A plenary panel on U.S. manufacturing of SSL products was moderated by Brodrick, who asked the overarching question, "What can be done to keep jobs in the U.S.?"

The panel was kicked off by Keith Cook of Philips, who called the issue of U.S. SSL manufacturing "probably one of the biggest challenges facing industry today." He noted that Philips has 21 luminaire plants in the U.S, as well as one LED chip-making plant, and named labor cost as a major consideration for off-shoring. Cook noted Philips' desire to keep manufacturing in the U.S. if the process can be automated without losing too much flexibility. He said government incentives, as well as DOE's SSL program, can help increase SSL manufacturing in the U.S.

The next panelist to speak was Govi Rao of Lighting Science, which has manufacturing facilities in three U.S. states and does contract manufacturing overseas. Rao described the challenges to establishing large-scale SSL manufacturing in the U.S., discussing market adoption cycles, the need to set and adopt standards, and the need to establish guidelines for quality metrics. Rao suggested the likelihood of a phased approach to more U.S.-

based manufacturing. “As the volume goes up, we may move to another type of supply chain,” he said, noting that as the scale increases, manufacturing locally for local distribution becomes a better option.

Kevin Willmorth of Lumenique followed with a discussion of the 300-plus independent lighting manufacturers in the U.S. Most have gross sales of less than $35 million and are make-to-order operations rather than make-to-inventory. Willmorth noted that such companies have historically been a source of innovation in applied lighting technologies, and that many of them “are emerging out of nowhere because of SSL.” He suggested a number of things DOE can do to facilitate their involvement in SSL, including simplifying access to funds for developing innovations.

Robert Harrison of Osram Sylvania gave his company’s perspective on the issue of U.S. manufacturing. He reviewed the scope of Osram Sylvania’s worldwide operations, noting that they have plants in Kentucky and New Hampshire and another opening in Pennsylvania. “We’re very interested in keeping jobs in the U.S. whenever it’s fiscally responsible to do so,” he said. Harrison stated that considerations involved in choosing a manufacturing location include quality, costs, supply chain, support, and the capability to keep up with updates in LED technology.

The panel presentations concluded with Heng Liu of Bridgelux, who observed that his company spent six months exploring where and how to place new manufacturing capacity, and ultimately decided to build epitaxy and chip capacity in the U.S. He said the potential for U.S. manufacturing depends on such things as getting the material cost down for epitaxy, decreasing the labor content of the chip, and developing tools to automate the manufacture of the LED package.

The panel was followed by a lively discussion period, during which audience members raised a number of topics and ideas related to the U.S. manufacturing of SSL, including innovation centers and zones, tax incentives, and driving U.S. demand for SSL. In response to a question about whether LEDs and OLEDs would compete with one another in the marketplace, the consensus — as affirmed by Harrison and Cook — was that the two technologies are so fundamentally different that they’ll be used for separate applications.

Attendees line up for a question and answer session with panelists.

3.1.6 Panel: Standards for SSL

Eric Richman, PNNL (Moderator); Kevin Dowling, Philips Color Kinetics; Pat Gardner, SEMI; Mike Hack, Universal Display Corp.

Panel moderator Eric Richman of Pacific Northwest National Laboratories noted that to date, most standards development has focused on performance rather than on manufacturing. Richman pointed out that federal rulemaking affects the manufacture and distribution of appliances, including lighting, but that LEDs are not currently on the list for proposed federal rulemaking. He reviewed DOE's support of SSL standards development, ranging from hosting workshops like the present one to identifying standards needs through programs such as CALiPER.

Next, Kevin Dowling of Philips Color Kinetics reviewed current SSL standards under development in the areas of nomenclature, photometry, color, eye safety, safety, interconnects, and controls and drivers. Dowling raised the issue of reliability, noting that true lifetime is related to reliability and that "mean time to failure" must be taken into account. He also provided a brief overview of the role of standards in California's Title 24 Energy Efficiency Standards for Residential and Nonresidential Buildings, and the U.S. Green Building Council's LEED (Leadership in Energy and Environmental Design) rating system. In conclusion, he underscored the need for accredited laboratories qualified to test products to new SSL standards.

Mike Hack of Universal Display Corporation then discussed the timing for development of standards for OLED lighting. While OLED technology is not as fully developed as LED lighting, and most would argue there is not yet a need for standards, Hack noted that OLEDs can benefit from the learning curve of LED standards. He suggested the OLED community become involved early with standards-writing organizations, to help plan for the standards that will eventually be needed for OLED general lighting. "Right now is probably the right time to get started," he said.

The standards panel concluded with Pat Gardner of SEMI, who drew on his organization's experiences in the semiconductor industry over the past 30 years to make a case for standards and collaboration in the manufacturing of high-brightness LEDs. He suggested that existing standards be reviewed for their applicability to high-brightness LED manufacturing, and that the "what, when, and who" of standards development be determined. Gardner said that beginning a standards dialog will facilitate international patent cross-licensing where appropriate, improve communication throughout the supply chain, reduce costs, and accelerate innovation.

Following the presentations, the audience engaged the panel members in discussions elaborating on various issues related to standards. The point was made that for some things, standardization that takes place too early can stifle innovation, but that in SSL manufacturing there is at present ample scope for the development of standards that would drive down costs.

3.2. LED Track

The LED track at the Vancouver workshop included detailed presentations on such topics as power supply and driver issues, the optimization of manufacturing equipment, and substrates.

3.2.1 Introduction to LED Track

Steve Bland, SB Consulting

The LED Track presentations were introduced by Steve Bland, who outlined the format of the April workshop in Fairfax and reviewed the LED roadblocks set forth in the strawman roadmap.

For packaged LEDs, roadblocks include cost, quality, and choice of substrates; uniformity, throughput, understanding, and efficiency of epitaxy; automation, cost of ownership, and yield of equipment; and testing, characterization, and metrology of process control. Roadblocks for LED luminaires include LED device variability/binning, cost and specification of the power supply/driver, uncertainty in long-term performance, cost of product testing, and standards.

Noting that the Vancouver presentations were intended to complement the Fairfax presentations and to address gaps and revisit key issues, Bland sketched the general plan for the LED portion of the Vancouver workshop.

3.2.2 Integrated Light Engines

Chuck Berghoff, Optoelectronix

Chuck Berghoff of Optoelectronix followed with an examination of SSL light engines, from the LED board, to optics, to electronics, to mechanical and thermal management. Berghoff explained how SSL technology is disruptive to the entire lighting supply chain, which is based on “dark” fixtures into which replaceable bulbs are inserted. He reviewed the challenges of bridging LEDs and the traditional luminaire world, noting the luminaire industry’s large and fragmented state, with thousands of high mix/low volume SKUs and 1,600 U.S.-based manufacturers, nearly all of whom are oriented toward traditional luminaire technology rather than SSL. Electronic design is not a core competency for most lighting manufacturers, who are used to metal, glass, a socket, two wires, and a plug. Even within the LED world there are gaps to bridge, since LED components have historically been used to make electronic equipment and customers have been electronics engineers.

Berghoff examined the obstacles to SSL luminaire adoption, including a rapidly changing technology and the lack of industry-wide standards for binning, packages, optics, drivers, and controls. He noted that quality and reliability issues are dependent on peripheral design elements including component selection, electronics circuit design, and thermal management design. In discussing costs, Berghoff pointed to the fact that, as Haitz observed, price comes down as the technology improves.

3.2.3 Power Supply and Driver Issues

Julio Vera, Philips Solid State Lighting North America

Julio Vera of Philips Solid State Lighting North America explored power supply and driver issues. He defined the driver as “the ballast that we use for LED solutions,” whose fundamental purpose is to drive the LED array at a specific voltage and current. He noted that the driver regulates power to counter system fluctuations, and that it isolates the LED system from high voltage to reduce shock hazard and increase safety.

Vera described the basic types and classes of LED drivers, comparing their advantages and disadvantages and reviewing their prevalence in various parts of the world, before looking closely at the issue of surge protection. He noted that in a typical LED system, the LEDs are mounted to a heatsink, which is connected to earth ground for thermal reasons. A common mode surge voltage of 10KV would break over the insulation between the LEDs and the heatsink in most installations, and therefore voltage clamping is required.

Vera pointed out that the typical breakdown of the LEDs to the heatsink is in the order of 2KV, so clamping below this level is necessary even if the driver is designed to handle higher voltages. This is why a driver design that can handle 10KV surges does not help the system past 10KV.

He noted that the voltages must be clamped to a level that the LED-to-heatsink insulation can safely withstand, to prevent LED failure, and that not clamping the common mode surges would put a large burden on the wiring inside the fixture, as everything (wires, connectors, wire nuts, etc.) would need to be designed to withstand 10KV.

3.2.4 Manufacturing Equipment Optimization

Andy Hawryluk, Ultratech

Andy Hawryluk of Ultratech followed with a talk emphasizing the importance of specialized manufacturing equipment, which he said can bring down SSL costs by lowering equipment costs; improving utilization, throughput, and overall yields; and automating the manufacturing process.

To provide historical perspective, he examined the manufacturing path of earlier-developing industries, including front- and back-end semiconductor, thin film heads (hard disk drives), and flat panel displays and high-volume microelectromechanical systems. Each of them started within the U.S. and then moved to Southeast Asia to reduce labor costs, because in the early stages their volumes were insufficient to attract an investment by tool manufacturers to produce productive manufacturing tools. Once these industries grew, tool companies provided productive, automated manufacturing tools that no longer required expensive labor.

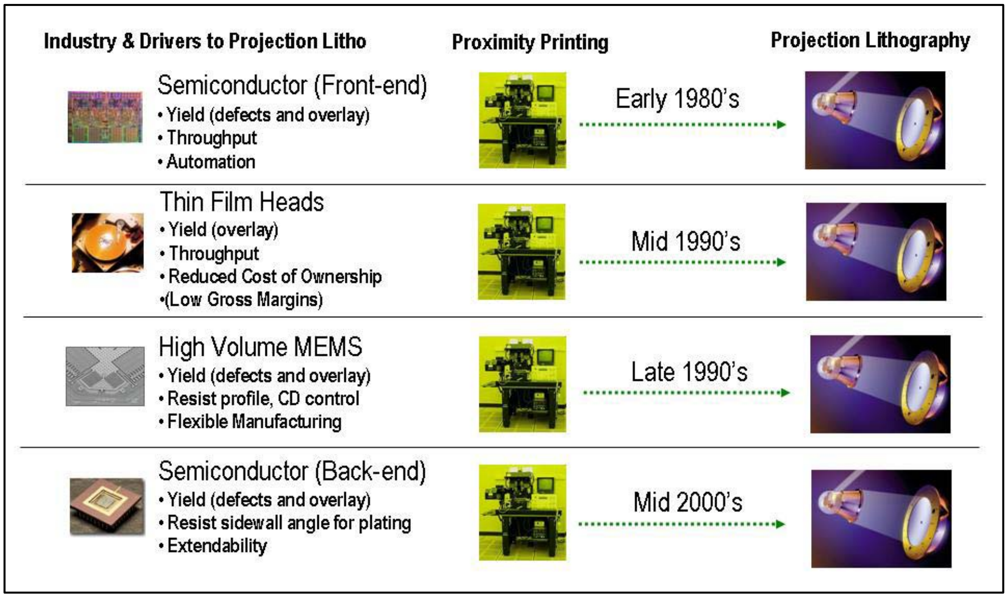


Figure 7: Manufacturing path of earlier industries for higher productivity tools – case study: lithography

Hawryluk reviewed the reasons for migration from proximity print to projection lithography in terms of throughput, overlay, line-width control, automation, mask costs, capital expenditures, and cost of ownership. He noted that historically, LED costs have decreased roughly 20-fold per decade, driven primarily by enhancements to LED efficiencies; however, continuing on the same cost reduction curve will require manufacturing improvements.

Noting that manufacturing tools have driven 500-fold price reductions in processed silicon, he stated that keeping the LED manufacturing industry domestic will require productive tools now. "If we can do something to reduce the labor content early, it's very conceivable that we can keep the LED manufacturing industry within the United States," Hawryluk said.

He stated that improving front-end manufacturing costs will leverage back-end costs and reduce LED lighting costs, and focused on lithography as a case study in manufacturing equipment optimization. Comparing the advantages of projection lithography and contact lithography, Hawryluk concluded that projection lithography provides a lower cost of ownership.

3.2.5 Inspection and Testing

Rich Solarz, KLA / Tencor

Rich Solarz of KLA / Tencor, a supplier of in-line LED inspection tools, spoke about in-line process control and yield management for the high-brightness LED industry. He noted that for the past few years, the LED industry has done better than Haitz's Law has predicted for cost reduction and technology improvement, and said he thinks DOE's SSL program played a significant role in facilitating this progress.

Reviewing cost-reduction centers for yield management, Solarz observed that cost reduction is not due only to replacing in-line human inspection with automated inspection for final product disposition. Cost reduction is roughly one-third due to product development, one-third due to factory ramp, and one-third due to improved yield at full scale production. Solarz noted that excursion flagging and process control dominate the yield for mature processes in production.

He discussed defect source analysis (DSA), focusing on its methodology and implementation. Key issues of DSA implementation include tool-to-tool coordinate accuracy transfer, binning transfer tool to tool, noise cluster treatment, user visualization, and matching.

Solarz said that adoption of tooling from other industries has provided value, but that customizing tooling to the high-brightness LED industry will accelerate cost reduction.

3.2.6 Sapphire Substrates Roadmap

Sunil Phatak, Rubicon Technology (delivered by proxy)

Sunil Phatak of Rubicon Technology was unavoidably detained; Steve Bland, acting as his proxy, presented Phatak's presentation on sapphire substrates.

Phatak's presentation noted that sapphire is used for 85 percent of blue/white LEDs, and that significant investment in sapphire-based LED technology is continuing. Key requirements for substrates for high-brightness blue/white LEDs were reviewed, such as being compatible with (AlGaIn)N lattice and TCE; mechanically rugged, inert, and stable in a MOCVD environment; transparent to UV, blue, and green wavelengths; manufacturable on a commercial scale and inexpensive; and readily available in high volumes and large diameters (50, 76, 100, 150, 200 mm). The GaN MOCVD process is proven, established, and high-yield, and crystal growth technology is scalable.

Phatak's presentation stated that sapphire is the only proven material for large-diameter LED substrate mass production, and it outlined the production process for sapphire substrates.

The industry is moving to larger-diameter wafers for several reasons — cost reduction, improved LED lamp performance (through larger chip sizes), growth for high-power

LED applications, the rapid development of large-diameter LED processes and equipment, and wafer availability. The presentation concluded with a review of the challenges of moving to larger-diameter wafers as well as possible solutions.

3.2.7 Freestanding GaN Substrates

Scott Zimmerman, Goldeneye

Scott Zimmerman of Goldeneye gave a talk on low-cost nitride device production using freestanding GaN substrates. Asserting that the “old” objections about GaN substrates (e.g., high cost, no volume supply chain, doesn’t work well in existing equipment, customers accept the status quo) are no longer valid, he called freestanding GaN “the best path to low-cost, high-volume production” and declared that there’s a U.S.-based supply chain already in place.

Zimmerman said switching to GaN substrates not only results in higher internal quantum efficiency, less droop, and longer life, but through the of thin freestanding GaN, can increase throughput and reduce cost by as much as tenfold, eliminate binning, and facilitate standardization. He noted freestanding GaN’s potential for use in producing solar energy, as well as with power electronics.

The major barrier to using thin freestanding GaN substrates, Zimmerman said, is the fact that billions of dollars have been invested in the present infrastructure. He said that thin freestanding GaN can be ramped to and cooled from growth temperatures almost instantaneously; enabling a 30-minute growth cycle. According to Zimmerman, use of rectangular GaN foils yields more good die than wafers, can cost less than sapphire, and can deliver the cost of HVPE and performance of MOCVD with 10 times higher throughput and yields.

Zimmerman said that the U.S. has significant domestic HVPE technical and manufacturing capabilities that can and should be leveraged, and that the elimination of binning and drastic reduction in die costs using freestanding GaN and semi-continuous reactor designs can enable light sources which reduce back-end processing costs to a level at which domestic manufacturing can compete with overseas manufacturing.

3.3 OLED Track

The OLED track at the Vancouver workshop included detailed presentations and panel discussions on vacuum processing, solution processing, and substrates and encapsulation.

3.3.1 Introduction to OLED Track

J. Norman Bardsley, Bardsley Consulting

Track chair Norman Bardsley of Bardsley Consulting set the stage for the OLED sessions by listing a number of challenges facing the OLED manufacturing industry, such as improving cycle time, yield and quality control, materials utilization, and equipment costs. He also formulated questions that would need to be answered concerning the process, stating that addressing these will make the roadmap targets more reachable. Bardsley then introduced the first panel members, who provided their concepts and strategies for addressing the challenges in manufacturing process using vacuum or dry processing.

3.3.2 Panel: Vacuum Processing

Mike Hack, Universal Display Corp.; Uwe Hoffmann, Applied Materials; Michael Long, Eastman Kodak; Gopalan Rajeswaran, Moser Baer

J. Norman Bardsley (standing) introduces the Vacuum Processing Panel (left to right): Michael Long, Eastman Kodak; Gopalan Rajeswaran, Moser Baer; Mike Hack, UDC; and Uwe Hoffmann, AMAT.

Uwe Hoffmann of Applied Materials initiated the panel discussion by presenting a manufacturing strategy concept for vacuum processing. He first provided an update on the status of OLED display versus lighting manufacturing, noting that several display production lines exist, whereas only one product is in the lighting market thus far. Because costs remain high for both, reducing manufacturing costs would need to come through increasing organic material utilization, increasing the substrate size, and by achieving higher throughput. Hoffman stressed that a near-term manufacturing strategy should include a modular design in order to enable the integration of other sources and technologies as they progress. The strategy used a phased approach to move from prototype to production, beginning with installation of a mid-volume production coater and using standard patterned substrates. To develop process and production know-how, Hoffman recommended producing a small number of sample prototype OLEDs for lighting using a mid-volume Gen 2 source, then upgrading to Gen 4 for small volume of production. The final step is to increase volume with additional coating and masking chambers, but keeping the existing sources to produce cost competitive lighting products.

Gopalan "Raj" Rajeswaran of Moser Baer followed with a concept for a U.S. pilot line and commercial products, based on lessons learned from pilot-to-production experience in display manufacturing in Gifu, Japan. Raj recommended using a flexible equipment configuration, with co-located but separate equipment. He also advocated an integrated manufacturing approach, which uses the pilot line as a baseline platform for introduction of more advanced technologies, and quickly introduces products that are designed concurrently to customer specifications. In addition, he reviewed the scale risks of a Gen 2 versus Gen 3.5 OLED lighting pilot line, and noted the importance of developing key supply chain partnerships in equipment, materials, and customers, as well as a mutually beneficial relationship between private industry and government in developing a pilot line.

Based on this experience, Rajeswaran recommended a manufacturer select two or more lead U.S. customers who can set unit product specifications, develop, and commercialize lighting products for consumers, preferably for an OLED luminaire module manufactured by the pilot line.

Next, Michael Long of Eastman Kodak presented a novel approach for overcoming the challenge of increasing vacuum deposition, while also increasing utilization and reducing downtime. He showed that in order to achieve the roadmap targets with vacuum processing, OLED manufacturing will require 11X faster deposition with 3X wider substrates. This presents a significant scale-up in vapor generation capability — without increasing decomposition. Long warned that degradation increases rapidly with increasing temperature and high deposition rates and that an elegant approach is needed given existing technology to avoid thermal decomposition. As a solution, Long presented Kodak's method that keeps the organic materials cold until it is needed — a vaporization on demand approach.

Mike Hack of Universal Display Corp. concluded the panel presentations by offering UDC's vision for OLED lighting manufacturing. He echoed the previously mentioned need for high material utilization and deposition rates, and lower cost equipment. In the context of a domestic manufacturing role, Hack noted that while the U.S. has a large number of luminaire manufacturers and OLED infrastructure expertise, there are no U.S. OLED panel manufacturers and that Europe and Asia are investing heavily in this area. In presenting a route for U.S. manufacturing to produce and demonstrate competitive prototype production, Hack stressed the need for a government role to grow OLED

OLED session participants listen to panelists.

manufacturing infrastructure, develop a pilot facility that can demonstrate and solve process integration issues, and promote development of advanced, low-cost manufacturing technologies. He also noted the importance of using existing technology, but making it modular. Hack closed by showing that in spite of the aggressive, long-term cost reduction targets, even with current high costs, niche products may still be a viable opportunity.

Following the presentations, the audience engaged the panel members in discussions that elaborated on their concepts and addressed additional questions. Various panel and audience members discussed possible ways to address the large capital investment barriers including a shared, combined R&D and pilot facility based on the collaboration of multiple firms. Another main topic discussed was how to specifically define yield, and how this would affect the roadmap target.

3.3.3 Wet, Solution, or Roll-to-Roll Processing

Vincent Cannella, ECD/United Solar Ovonic

Vincent Cannella of Energy Conversion Devices (ECD), which manufactures and sells thin-film solar laminates, spoke about equipment issues for processing roll-to-roll OLED lighting. According to Cannella, ECD solved the challenge of continuous roll-to-roll web production through successive plasma-enhanced chemical vapor deposition (PECVD) vacuum processes, keeping dopant gases separated from the intrinsic layers. This is the enabling technology that allowed the development of roll-to-roll PECVD production for amorphous silicon solar cells. Historically, this "gas-gate" technology was first developed to allow separation of gases between doped and un-doped vacuum deposition processes for simple PIN solar cells used in Sharp calculators. Following the development of this technology, ECD learned how to create more complicated structures using indium tin oxide (ITO), back reflectors, or triple junction amorphous silicon cells. The most recent development in the technology enabled the production of solar cells used for roof integrated applications. This production line was a 300-foot long triple junction PECVD line that can use 6 vertically oriented webs.

Cannella stated that, as demonstrated by GE, web processing can be fully integrated with all processes necessary to create solution-based OLEDs, including substrate cleaning; patterning of ITO; OLED deposition, patterning, and drying; and cathode deposition and patterning. Cannella noted that this technology is particularly useful for polymers and barrier coatings, because there is no contact at the front surface.

Parallels were drawn from ECD's experience integrating a wide range of roll-to-roll processes: web cleaning and conditioning, polymer coating, ovens and dryers, encapsulants and other film lamination, patterning processes, PECVD, vacuum evaporation, sputtering, web handling, speed and tension control, steering, coil handling, and other production equipment functions. Cannella concluded by confirming that the technology and expertise currently exists for both the equipment and processing roll-to-roll production of solution-based OLED lighting. It has been demonstrated in a prototype production line currently operating at GE — the next step would be development of a major manufacturing line in the U.S.

3.3.4 Panel: Solution Processing

Curtis Fincher, DuPont Displays; Devin MacKenzie, Add-Vision; Martin Yan, GE Global Research

The next panel delved further into the topic of solution processing for OLED manufacturing. Martin Yan of GE Global Research began by reviewing the benefits of solution-based web processing. He noted that equipment costs for dry processing tend to be higher than for web processing, especially at high throughputs. Because GE believes that cost is critical, the company chose the web-processing approach, developing a facility that uses as many commercially available techniques as possible. When a needed technique was not commercially available, GE created the technology, such as for the solution-assisted wipe. Yan also noted that GE designed the production line to be very flexible.

Devin MacKenzie of Add-Vision followed with a presentation on low-cost, high-efficiency printed polymer OLEDs for flexible applications and scalable manufacturing. He noted that the main benefit of polymer OLEDs is their ease of processing — for example, one can produce 30,000 square feet of OLED displays a month with a production facility that costs only $1 million. MacKenzie stated that almost 92 percent of the costs in web processing are for materials, which is why good substrates and barrier films are so important. He emphasized that compared to material costs, labor and depreciation are insignificant, and called material utilization one of the most important goals in achieving less expensive OLED panels. MacKenzie urged DOE to target its funds at creating more efficient polymer LEDs. Then, he named several key factors for print-based SSL, including the cost of solution-based active layer materials for low-cost coating/printing, cost and availability of substrates, defects, yield, inspection, and encapsulation.

The panel presentations concluded with Curtis Fincher, who provided DuPont Displays' perspective on the manufacture of OLED lighting. Fincher stated that although DuPont is a material supplier, it remains neutral on the issue of vacuum-deposited sheet processing or solution-processed web-processing.

He noted that although solution-based web-processing has a cost advantage over vacuum-deposited sheet processing, there is a perceived trade-off in performance, and that many companies are hesitant to adopt web-processing because it's not commonly used in the semiconductor industry. He countered both points by stating that web-processed materials can exhibit high performance, and that new manufacturing methods should be used because they are less expensive. Fincher concluded by stating that web-based solution processing appears to be a solid choice for OLED lighting.

In the ensuing lively discussion, attendees debated the various approaches, emphasizing issues with patterning, machine costs, and throughput. Some attendees attempted to clarify cost details that panelists hesitated to provide due to their proprietary nature. Facilitator Norman Bardsley helped focus the discussion on identifying real costs that could be discussed openly.

3.3.5 Substrates and Encapsulation

Tom Clausen, 3M

The discussion on substrates and encapsulation was sparked first with a talk by Tom Clausen of 3M. Clausen began by explaining required encapsulation system performance, and how in OLEDs, moisture degrades cathodes, causing dark spots.

He argued that an advanced barrier material, which addresses the need for a transparent high barrier with flexibility, would accomplish ultralow water vapor transmission. One known approach for addressing this is to multi-layer oxides with polymer. These advanced barriers are potentially feasible, but will require greater capital expenditures, as well as better measurement methods. Clausen asked, “If you can barely measure 10-4 g/m2/day (in about 100 hours) how do you make sure you make a quality product?”

The second portion of Clausen’s presentation concerned OLED light outcoupling. This is a major barrier to enhanced performance, as currently only about 20 percent of generated light is outcoupled. Clausen said 3M has two approaches to improving outcoupling: external and internal light extraction films. The company is currently sampling external light extractors, and expects commercialization in 2010. For internal light extractors, 3M is working with select partners on optimization, and Clausen anticipates product definition in 2010, with commercialization in 2011. Both can be combined with barrier film to make an integrated solution. The limitations of plastic substrates pose challenges, and collaboration with OLED lighting makers is critical for success.

Clausen then commented on costs. Plastic substrates are sold by weight, and many variations of plastic are being considered, so costs quickly become a major factor — is it just a piece of plastic, or is it a piece of plastic with an outcoupling layer, a hard coat, or some other option? “Depending on the temperature characteristics needed, there’s not a lot of margin for a company like 3M if you need to add a lot of these features. It would be good to have a better definition of what’s required, and to have a more realistic view of what it will cost,” Clausen concluded.

3.3.6 Panel: Substrates and Encapsulation

Michael Boroson, Eastman Kodak; Dennis O’Shaughnessy, PPG Industries; Martin Rosenblum, Vitex Systems, Inc.; Robert Rustin, DuPont Teijin Films

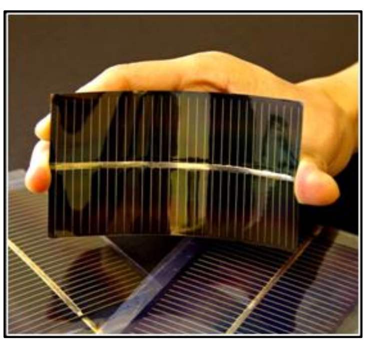
This panel provided a range of perspectives on substrates and encapsulation. Mike Boroson of Eastman Kodak first discussed substrates in more detail. Based on several assumptions, Boroson offered an analysis showing that a water vapor transmission rate of 1E-08 g/m²/day would be a more appropriate requirement than 1E-06 g/m2/day. He explained that a 1,000-fold improvement of the barrier film defect density, along with vast encapsulation cost decreases, are needed in order to make marketable products. He concluded that metal foil encapsulation is the only alternative that can meet SSL cost requirements.

Next, Dennis O’Shaughnessy of PPG Industries touted float glass as a viable substrate, noting that it is atomically smooth, greater than 90 percent transparent, and can be obtained at a fraction of the cost of display glass. He also noted that the float glass industry practices cost-effective manufacturing of large area functional coatings for transparent conductors such as ITO and SnO2:F, and light extraction technology, and that one should focus on value and systems solutions.

PPG float glass – a viable substrate

Bob Rustin of DuPont Teijin Films followed with a discussion of flexible substrates. He observed that because many problems with manufactured OLEDs result from unclean protection films, DuPont is currently working on “hygiene” issues associated with the films. Rustin said DuPont has found that crystalline materials exhibit improved moisture pickup, expansion, and contraction when compared with amorphous materials. He added that currently, these films can be processed, exhibit low moisture and shrinkage, and have smooth surfaces. However, several production challenges still need to be overcome, including developing the manufacturing capacity for these films, and measurement and control methods for the manufacturing process.

The panel concluded with a presentation by Martin Rosenblum of Vitex Systems, Inc., on flexible barrier films. He stated that flexible films are very useful for roll-to-roll manufacturing, and that Vitex has developed a flexible barrier film called Barix, which is compatible with downstream processes and meets physical, optical, and environmental criteria. Rosenblum said Barix can be used in an integrated product and has an appropriate topography and cleanliness, enabling it to be used for direct encapsulation. He observed that robust manufacturing and quality control are important when developing barrier films like Barix.



Flexible photovoltaics

Thin-film battery

J. Norman Bardsley then facilitated a brief question and answer period, explaining that performance requirements are not in the draft manufacturing R&D roadmap because they are addressed in the SSL Multi-Year Program Plan (MYPP). However, the OLED audience was invited to respond if these requirements are not appropriate.

3.4 Vancouver Workshop Process

Every presentation and panel discussion at the Vancouver workshop was followed by an open discussion period, during which all the attendees had the opportunity to ask questions and make comments. As in the Fairfax workshop a significant portion of the workshop was devoted to breakout sessions split into two tracks, one for LEDs and one for OLEDs.

LED Packages break out session

The breakout sessions were devoted to open discussion rather than formal presentation. Attendees focused on reviewing the draft SSL Manufacturing R&D Roadmap that had been created based on input from the Fairfax workshop, refining the priorities, and making recommendations for changes and additions. This feedback was addressed in a working version of the roadmap published in September 2009, which represents industry consensus on the expected evolution of SSL manufacturing, best practices, and opportunities for collaboration. The SSL Manufacturing Roadmap can be accessed online at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-manufacturing-roadmap_09-09.pdf .

4. NEXT STEPS

The SSL Manufacturing R&D Roadmap (September 2009) can be accessed online at http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl-manufacturing-roadmap_09-09.pdf . The roadmap is intended to guide DOE planning and future solicitations related to the new SSL manufacturing R&D initiative. The first solicitation was issued in June 2009, with selections anticipated in early 2010. In addition, the roadmap will serve as a guide for equipment and material suppliers, to reduce the risk and, ultimately, the cost of entering into SSL manufacturing.

With DOE continuing to invite industry participation and feedback, the SSL Manufacturing R&D Roadmap is expected to evolve to keep pace with the rapidly developing technology. The roadmap will be reviewed annually by DOE in collaboration with our industry partners and updated to reflect progress and changes in priorities. The next DOE SSL Manufacturing R&D Workshop is tentatively slated for April 2010. As it becomes available, additional information will be posted at www.ssl.energy.gov .

This collaborative feedback process is central to DOE's new SSL manufacturing R&D initiative, which has two primary goals: to enhance product consistency and quality and to accelerate cost reductions through manufacturing improvements. A third objective is to encourage domestic U.S.-based manufacturing of SSL products. As the R&D roadmap reflects, finding manufacturing approaches that are less labor-intensive — such as automation — can reduce the incentive to move the assembly process to regions of the world where the labor costs are low.

APPENDIXES

Fairfax Workshop List of Attendees, pps. 1 – 5
Vancouver Workshop List of Attendees, pps. 1 – 5

2009 Transformations in Lighting

SOLID-STATE LIGHTING MANUFACTURING WORKSHOP

April 21–22, 2009
Fairfax, VA

ATTENDEE LIST

Diane Allard
Akoya

Andrew Allerman
Sandia National Laboratories

Doug Anberg
Ultratech

Frazer Anderson
Oxford Instruments-TDI

Chris Andrews
Renaissance Lighting

Mehran Arab
PPG Industries

Abdul Aslami
Sharp

Susana Babic
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Mike Bailey
EcoLink

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QD Vision

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Bardsley Consulting

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Timothy Boles
MA-COM Technology Solutions

Michael Bremser
Permlight

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Paul Burrows
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Vincent Cannella
ECD/United Solar Ovonic

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Yuanning Chen

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Michael Ciesinski
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Keith Cook
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Randy Creighton
Sandia National Laboratories

Carl Crossland
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Mark D’Evelyn
Soraa, Inc.

T.J. de Jony
Exclara Inc.

2009 Transformations in Lighting
SOLID-STATE LIGHTING MANUFACTURING WORKSHOP
April 21–22, 2009
Fairfax, VA

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Brian Dlugosch
AIXTRON, Inc.

Thomas Dudley
Boston University

Anil Duggal
GE Global Research

Frederic Dupont
Soitec USA, Inc.

Ryan Egidi
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Kevin Elsken
Bayer Material Science

Keith Evans
Kyma Technologies, Inc.

William Feehery
DuPont OLEDs

Curtis Fincher
DuPont Displays

David Fleak
Tyco Electronics

Ben Frank
Totus Lighting Solutions, Inc.

Douglas Freitag
Bayside Materials Technology

Miguel Friedrich
NextechFAS

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Pat Gardner
SEMI

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Kevin Gauna
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Alan Geishecker
Renaissance Lighting

Amal Ghosh
eMagin Corporation

Bob Gibson
National Rural Electric Cooperative Association

Mark Gross
Pacific Northwest National Laboratory

Shiping Guo
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Mike Hack
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Monica Hansen
Cree, Inc.

Robert Harmon
Jabil Circuit, Inc.

Eric Haugaard
BetaLED

Andy Hawryluk
Ultratech

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Heinemann & Co. Inc.

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The Christopher Lighting Company

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Robert Hoffman
Carlsbad Photonics

Uwe Hoffmann
Applied Materials

Robert Hojnacke
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2009 Transformations in Lighting

SOLID-STATE LIGHTING MANUFACTURING WORKSHOP

April 21–22, 2009

Fairfax, VA

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Mike Krames
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Orb Optronix

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Amy Oriss
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Tim O’Sullivan
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greenTbiz – LEDs Magazine

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Pratik Patel
Artisan Partners

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Edward Patton
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Bruce Pelton
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Jeff Perkins
Yole Développement

Robert Peterson
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Edward Petrow
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Paul Pickard
Cree LED Lighting Solutions

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Lenny Sachs
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Bernard Scanlan
TDI

John Schober
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Dan Sperling
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Robert Steele
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Heidi Steward
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Alexander Usikiv
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Guy Vaccaro

Peter Van Poucke
Philips Innovative Applications

Steven VanSlyke
Eastman Kodak

Robert Visser
Applied Materials

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Bayer Material Science

Dieter Wagner
Applied Materials

George Wang
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Debra Wasser
Veeco Instruments, Inc.

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Radcliffe Advisors

Christian Wetzel
Rensselaer Polytechnic Institute

Kevin Willmorth
Lumenique

Craig Wright
Progress Lighting

Derek Xin
JG GreenTech Global

Martin Yan
GE Global Research

Jeremy Yon
Litecontrol

Barry Young
OLED Association

Scott Zimmerman
Goldeneye

2009 DOE SOLID-STATE LIGHTING MANUFACTURING WORKSHOP II

June 24–25, 2009
Vancouver, WA

_______________*ATTENDEE LIST*_______________

Diane Allard
Akoya

Doug Anberg
Ultratech

Frazer Anderson
Oxford Instruments-TDI

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Sharp

Karyn Atwood
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Pete Avila III
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Teresa Bair
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Tom Barnett
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Chuck Berghoff
Optoelectronix

Nathaniel Black
Black Box Energy, LLC

Steve Bland
SB Consulting

Andrew Bobel
Neptun Light, Inc.

Michael Boroson
Eastman Kodak

Dennis Bradley
GE Lumination

Michael Bremser
Brillia

James Brodrick
U.S. Department of Energy

Diana Burk
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Anthony Burrell
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Vincent Cannella
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Alan Chalmers
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Marc Chason
Marc Chason and Associates, Inc.

Kevin Chen
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Jim Christensen
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2009 DOE SOLID-STATE LIGHTING MANUFACTURING WORKSHOP II

June 24–25, 2009
Vancouver, WA

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