2010 DOE Solid-State Lighting

MANUFACTURING R&D WORKSHOP

April 21–22, 2010 • San Jose, California

SSL Manufacturing R&D Workshop

REPORT

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

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1. Introduction

More than 250 industry leaders from all corners of the supply chain – including chip makers, luminaire manufacturers, material and equipment suppliers, packagers, luminaire testers, and makers of testing equipment – gathered in San Jose, California, April 21-22, 2010, to share insights, ideas, and updates at the second annual Solid-State Lighting (SSL) Manufacturing R&D Workshop, hosted by DOE. This workshop is a key part of an initiative launched by DOE in 2009 to enhance the quality and lower the cost of SSL products through improvements in manufacturing equipment and processes and to foster a significant manufacturing role in the U.S. This year in San Jose, attendees explored a wide range of related topics and focused on reexamining and updating the DOE Manufacturing R&D Roadmap.

2. SSL Manufacturing Overview

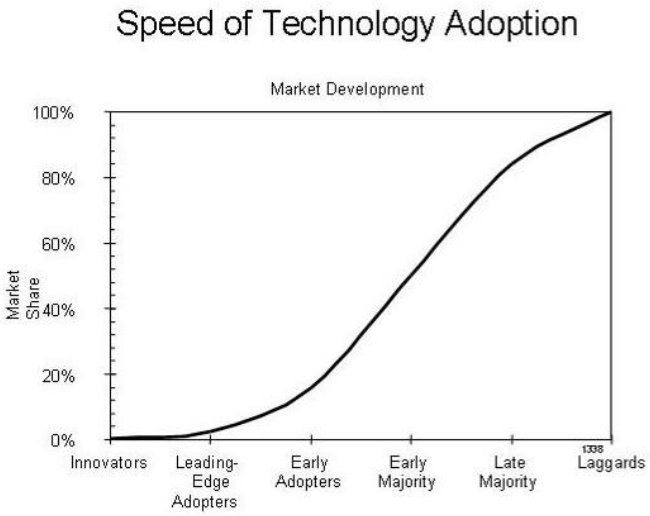
2.1 Welcome

DOE SSL Portfolio Manager James Brodrick kicked off Day 1 by providing an overview of the DOE SSL Manufacturing R&D Initiative, and progress to date. He noted the importance of the Manufacturing Roadmap, which resulted from 2009's inaugural SSL Manufacturing R&D Workshops, and complements and extends DOE's SSL R&D Multi-Year Program Plan. It identifies specific manufacturing R&D areas of need for LEDs and OLEDs, defining clear plans, timetables, and metrics to address major barriers. Brodrick noted that whereas last year's roadmap defined where we wanted to go, this year's focus is on what needs to be done to get there. He emphasized the participatory nature of the workshop and told attendees "Your guidance is very, very important." Brodrick concluded with a preview of the next two days:

- Plenary talks and panel sessions would expand on critical issues and barriers
- R&D presentations and a poster session would preview the first round of DOE-funded manufacturing R&D projects
- Parallel track sessions for LEDs and OLEDs would refine roadmap tasks and priorities.

2.2 World Status of SSL Manufacturing

Vrinda Bhandarkar of Strategies Unlimited followed with an update on SSL manufacturing trends worldwide. Outlining the high-brightness (HB) LED industry structure, she noted that most HBLEDs are packaged in Asia, and observed that although design approaches for LED fixtures and light engines are becoming more sophisticated, product interfaces haven't been standardized, and poor quality is still a major issue. Bhandarkar made the point that many LED lighting fixtures are designed in the U.S. or Europe, but a high percentage are made in China. While in part due to government incentives, Chinese manufacturing is also fostered by a highly developed infrastructure that often allows a single contractor to do the entire job, as well as China's proximity to the supply chain and high-growth markets.



External stimulus, as well as increases in scale, help bring down the high initial cost of any new technology.

2.3 The Impact of Infrastructure on Global Manufacturing Decisions

Jim Anderson of Philips Color Kinetics discussed the impact of infrastructure on global manufacturing decisions. He predicted that LED lighting will dominate the market by 2020, and that "smart systems" with integrated controls and sensors will play an increasingly important role, along with field-serviceable modular components. Anderson said he thinks there will be a significant SSL manufacturing base in North America, with luminaires being finished here using components that are made in other regions. In reviewing the infrastructure needed for SSL manufacturing success, he cited a network of universities, professional associations, and laboratories; a pool of relevant skills and talent; and project grants, funding, and tax incentives.

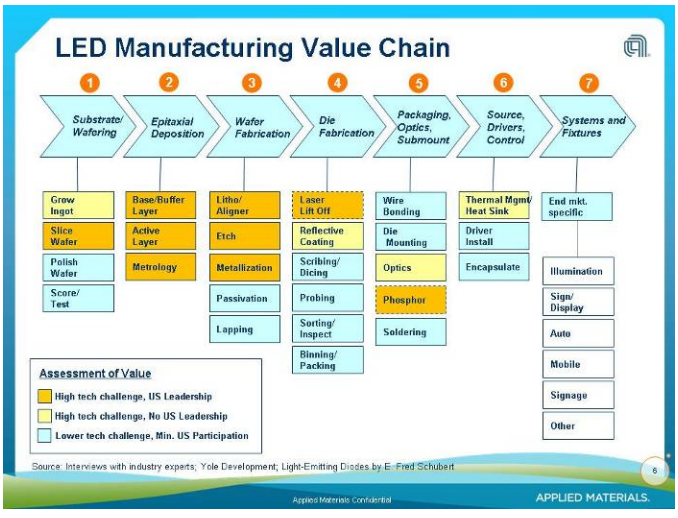
Jim Anderson explores how infrastructure impacts global manufacturing decisions.

3. Preview of the First Round of DOE SSL Manufacturing R&D Awards

3.1 Research Previews

Each of the recipients of DOE's first eight SSL manufacturing R&D awards outlined what they plan to accomplish with their projects, which range in focus from epitaxy tools, to automated defect detection systems, to the design and setup of OLED manufacturing pilot lines. These awards, which total more than $20 million in American Recovery and Reinvestment Act funding, were first announced in January 2010 and reflect DOE's new commitment to accelerate the adoption of SSL technology through manufacturing improvements that reduce costs and improve quality.

Nag Patibandla of Applied Materials Inc., discussed his company's plans to develop an advanced epitaxial growth system for gallium nitride LED devices that will decrease operating costs, increase internal quantum efficiency, and improve binning yields. The operating costs, he explained, will be lowered by decreasing cycle time, increasing throughput, and reducing the cost of chemicals. The internal quantum efficiency will be increased by reducing the density of extended defects and point defects. Binning yields will be improved by improving the uniformity of wavelength and output power — not only within the wafer, but from wafer to wafer and from run to run. Patibandla reviewed the key aspects of his team's



Nag Patibandla shared Applied Material's assessment of SSL manufacturing opportunities, noting that yield is the No.1 cost issue.

technical approach, including creating a multi-chamber system, automated *in-situ* cleaning of the deposition chambers, controlling the growth temperature with lamp heating, and reducing material defects by taking advantage of the flexible configuration of Applied Material's Centura platform.

Jie Liu of GE Global Research described his company's plans to develop, within the next two years, a roll-to-roll solution-processing method for producing small-molecule OLEDs, using as a starting point an existing polymer-based machine. He reviewed the two basic ways OLEDs are made: dry-coated, in which the organic layers are thermally evaporated; and wet-coated (or solution-processed), in which they're coated or printed from solution. Liu explained that although there have been recent advances in both methods, dry-coating is the more mature technology and typically involves more layers than solution-processing, which has a slower development cycle but the potential for much lower cost. He described the machine Global Research currently uses to produce roll-to-roll OLEDs with polymers, and noted that it will be modified for compatibility with small molecules, in partnership with DuPont Displays, to achieve his project's goal of proving that highest-performance wet-coated small molecules can be made roll-to-roll.

Anirudha Deshpande of GE Lumination talked about his company's plans to develop, design, and pilot advanced manufacturing methods for warm-white general-illumination LEDs, based on remote phosphor techniques. The project involves GE's patented modular Vio remote-phosphor white LED emitters, which he said are designed for performance, ease of manufacturing, and scalability and offer excellent correlated color temperature maintenance as well as lumen and color uniformity, plus minimal color shift with increasing drive current. Deshpande outlined the project tasks, which involve evaluating remote-phosphor manufacturing methods and selecting one of them, designing and piloting high-speed characterization techniques, and designing a volume production line. He said the manufacturing methods being developed could reduce overall costs by as much as 53 percent.

Srini Vedula of KLA-Tencor Corporation discussed the use of automated inspection to increase yield and decrease defects and cost in SSL manufacturing. He explained how cost reductions of approximately twofold are possible with improved process control, through accelerated development and ramp, improved baseline yield, and faster excursion detection. In high volume HBLED manufacturing, the economic impact from minor process excursions (<5 percent yield loss) is usually much higher than that from major process excursions (>20 percent yield loss) due to increased frequency of occurrence. Vedula noted that automated inspection reduces the number of wafers at risk and permits earlier detection of "killer" defects. He outlined the key milestones his project hopes to achieve, including improvements in tool sensitivity, advanced defect detection and classification, and integration of all process information, from back end to front end.

Michael Craven of Philips Lumileds Lighting Company, LLC, described his company's plans to use nitride epitaxy on 150mm silicon substrates to produce low-cost, high-performance warm-white general-illumination LEDs. He compared sapphire and silicon as LED substrates, noting the advantages and disadvantages of each, and reviewed the project's goals. These include reducing epitaxy costs by 60 percent by replacing sapphire substrates with silicon and scaling the epitaxy process to 150mm to increase throughput, as well as simplifying white LED binning by reducing pump wavelength distribution by 20 percent. But Craven cautioned that these objectives "are for naught, unless we can maintain warm-white LED lm/W performance and reliability."

Andy Hawryluk of Ultratech Inc., talked about his company's plans to adapt an existing lithography tool that was designed for the semiconductor industry for use in manufacturing high-brightness LEDs, in the process reducing capital expenditure and cost of ownership while increasing throughput and yield. He described Ultratech's existing lithography tool, and said that its throughput can be improved substantially by means of a higher-brightness illuminator. Hawryluk noted that LED substrates are often warped from the MOCVD process, but that by using die-by-die alignment and wafer warpage mapping, the die can be correctly located and the wafer tipped or tilted to achieve better overlay. He said he expects to have this tool available for advanced manufacturing within two years, and predicted that, to support high-volume manufacturing, the entire industry will eventually use such tools.

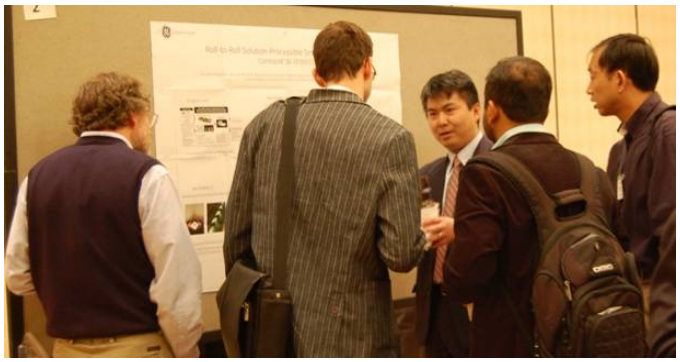
Andy Hawryluk made the case that although LED cost reductions to date have been driven by improvements in efficiency, manufacturing improvements will be needed if the downward cost trend is to continue. He noted that manufacturing tools have driven a 500x price reduction in processed silicon since 1968, and the same approach could be applied to LEDs.

Mike Hack of Universal Display Corporation (UDC) talked about his company's plans to facilitate the growth of the embryonic OLED lighting industry in collaboration with Moser Baer Technologies. Moser Baer Technologies is setting up a pilot OLED manufacturing line in the U.S. that will provide prototype lighting panels to U.S. luminaire manufacturers. Hack explained how UDC will scale and transfer UDC's phosphorescent OLED technology to the high-throughput pilot line — which will be based on known and proven manufacturing processes — and which he expects to be up and running within a two-year time frame. Hack described the simple all-phosphorescent, single-stack device architecture of the OLEDs, and noted that the 150mm x 150mm panels will enable manufacturers to test design concepts and consumer acceptance of lighting products.

Bill Quinn of Veeco Instruments described his company's plans to drive down the cost of high-brightness LEDs by implementing process simulation tools and temperature control methods to increase yield, and by improving temperature measurement and control. He explained how Veeco will incorporate an advanced chemistry model developed by Sandia National Laboratories into its own computational fluid dynamics models to improve reactor design and efficiency, and will use Sandia's near-ultraviolet and mid-infrared pyrometers to improve MOCVD temperature uniformity and repeatability and increase yield. Quinn said that the two-year project should improve within-wafer uniformity as well as wafer-to-wafer and run-to-run repeatability, and combined with planned increases in productivity, LED epitaxy costs will be reduced by a factor of four.

3.2 Poster Session

Attendees got an opportunity to dive into the details and talk to these presenters one-on-one at a poster session and reception sponsored by the Next Generation Lighting Industry Alliance (NGLIA) and Philips Lumileds Lighting. To kick off the reception, San Jose mayor Chuck Reed talked about his city's focus on clean technology. NGLIA chair Keith Cook of Philips gave some background on NGLIA, an alliance of for-profit corporations formed to accelerate SSL development through government-industry partnership, and invited attendees to join.



Jerry Liu discusses GE Global Research's roll-to-roll solution-processing method at the poster session/reception.

3.3 DOE Funding Opportunities: How to Prepare a Comprehensive Proposal

Brian Dotson of the National Energy Technology Laboratory offered some straightforward guidance on how to assemble and deliver a comprehensive proposal for DOE SSL funding. He reviewed the application evaluation process and presented guidelines and helpful suggestions on preparing an application – such as providing clearly described research and goals, offering ideas that are responsive to the funding announcement's areas of interest, and thoroughly addressing all aspects of the evaluation criteria.

4. Panel 1: Designing for Manufacturability

A panel moderated by Steve Bland of SB Consulting discussed ways in which industry can improve the design of SSL products to make them more manufacturable, focusing on what's currently being done along those lines, and how such changes might lead to cost reductions. Len Levy of OSRAM Sylvania reviewed a number of key elements that will accelerate SSL adoption and must influence its design, including flexibility, conversion, interoperability, and infrastructure. In addition to designing products for manufacturability, he emphasized making test requirements specific to SSL sources and electronics, utilizing supply chain optimization processes, focusing on factory systems and operational processes, and conducting cycle-time sensitivity analyses.

Len Levy of OSRAM Sylvania talks about how to make SSL products more manufacturable.

Mark Hodapp of Philips Lumileds Lighting discussed evaluating the lifetime behavior of LED systems, making the point that understanding component reliability enables LED system cost optimization, and noting the usefulness of good reliability and maintenance models. He emphasized that the LM-80 test report alone is not sufficient for determining system reliability because the data needs to be extrapolated to the luminaire's lifetime, and stressed that manufacturers should be able to provide lumen maintenance and catastrophic failure models at specified user conditions.

Paul Pickard of Cree presented an integrated approach to LED manufacturing as one way to drive down costs. He explained that simplifying SSL luminaires through an integrated approach in the areas of LED chips; components; and thermal, optical, and electrical design can provide high quality and performance at low cost, noting that subsystem optimization without regard to system integration won't deliver the expected cost reductions. Pickard stated that while standardizing can simplify the process of developing an SSL product, standardizing too much too early can stifle innovation and unnecessarily drive up costs.

Yuan-Sheng Tyan of TCE OLED discussed how to reduce SSL manufacturing cost by designing the device to have low material cost and high yield. He focused on doing this through incorporating four technology elements: monolithic structure, tandem architecture, internal extraction structure, and short reduction layer. Tyan made the point that cost reduction cannot compromise fitness to use, and that in high-volume manufacturing, materials cost and yield determine the ultimate cost. "We have to make devices that are competitive against all the other lighting technologies," he stressed.

Question and Answer Session
In the Q&A session, Pickard was asked whether he had figures for the cost of testing, and he said Cree includes its cost of testing in the cost of assembly. Another questioner asked whether the lifetime of an LED luminaire should be based on the most failure-prone component, if LEDs aren't the weakest link. Hodapp's response was that if the weakest link is known, there's no point in having the other components last longer than that link, but that an option is to improve the weakest link so that it lasts as long as the other components.

5. Panel 2: Changes in SSL Manufacturing

Day 2 began with a panel discussion on how SSL will change luminaire manufacturing. Moderated by Morgan Pattison of SSLS, Inc., the discussion focused on how the present infrastructure will change; what the implications are of moving to a more complex, integrated system; how to ease this transition; and what the special needs of smaller luminaire manufacturers are.

Dennis Bradley of GE Lighting Solutions discussed the new manufacturing environment for SSL. "I really believe that U.S. manufacturing has become more viable with solid-state lighting luminaires," he said, observing that the percentage of labor content is very small compared to the overall cost. Bradley made the point that overall system reliability depends on multiple factors and not just on the LEDs, and emphasized the importance of serviceability. He gave the opinion that market expectations for SSL performance are "staggeringly high," and said that products don't have to outperform incumbent technology in every single respect.

Eric Haugaard of BetaLED offered the perspective of a manufacturer that's migrated to SSL from high-intensity discharge (HID) technology for outdoor lighting applications. He discussed product performance expectations for SSL luminaires, noting that longer service interval requirements require manufacturers to pay attention to such aspects as finish, leak resistance, and long-life materials. Haugaard emphasized the value of scalability, which allows for small increments of change in luminous intensity, as well as the importance of performance assurance and documentation.

Peter Ngai of Acuity Brands Lighting focused on OLED luminaires, which he explained are simpler in structure than LED and conventional luminaires. He compared the cost of lamp replacement relative to luminaire cost for the three technologies (-10% for conventional, 30%+ for LED, 50%+ for OLED), and observed that the higher this relative cost, the lower the likelihood of users accepting a high frequency of lamp replacement. Ngai predicted that the life of SSL light sources will gradually increase until they last

as long as the luminaire's service life, but that the service life won't exceed 10 years or 40,000 hours, because rapid technological advances during that interval will make users want to replace previously installed systems.

Michael Bremser of Permlight Products Inc. described a number of problems and potential solutions in key areas of SSL manufacturing. For example, he pointed out that although luminaire manufacturers aren't set up to make SSL fixtures, and that component suppliers are looking for much higher volume than the current market warrants, standard light engines with standardized connections can help by minimizing soldering and physical connections. To deal with the problem of shortages of electrical components, Bremser suggested that luminaire manufacturers qualify a second source before there's an emergency, and that they forecast their needs accurately.

Question and Answer Session
In the Q&A session, one attendee wondered whether the technology exists to make the components of an LED luminaire match the performance of the LEDs themselves, since LEDs are a more efficacious light source than anything previously developed, and the problem seems to lie in the balance of the system. Bradley explained that a big part of the problem is cost. "You can make a driver that will last a long time, but it will cost a lot more," he said. Another attendee asked what role government legislation will play in helping SSL become a reality, to which Haugaard replied that the industry, like all others, is motivated by greed, so what's needed are ways to help people make more money. "People feel good about being green," he said, "but they feel better if the green is from dollars."

6. Updating the SSL Manufacturing R&D Roadmap

6.1 Review of Proposed Updates

Fred Welsh of Radcliffe Advisors previewed the proposed updates to the DOE SSL Manufacturing R&D Roadmap, which were based on feedback from a series of roundtable discussions held in March 2010. To view the roundtable reports, visit http://www1.eere.energy.gov/buildings/ssl/techroadmaps.html.

6.2 Break-out Tracks

Workshop attendees split up into separate LED and OLED track sessions, where they discussed these proposed updates in detail, exploring the related issues in depth. Also discussed at length were proposed tasks distilled from the March 2010 Roundtables that might be suitable for funding support, including luminaire/module manufacturing, phosphor manufacturing, phosphor application, test and inspection equipment, tools for epitaxial growth, LED packaging, and driver integration and manufacturing. Workshop attendees were invited to review those tasks, suggest clarifications or changes in the descriptions, and add more detail to the metrics, identifying the status and reasonable goals and timelines.


Attendees in LED (left) and OLED (right) breakouts provide valuable input for the next R&D Roadmap.

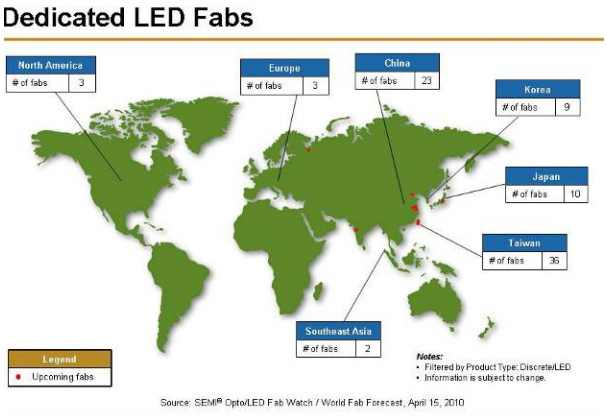
In order to enable richer discussion of the issues and make it easier for more voices to be heard, the track sessions were themselves split up into issue-specific subgroups. The input from these track sessions will be used to update the SSL Manufacturing R&D Roadmap and guide DOE planning for Manufacturing R&D solicitations. DOE expects to publish the updated roadmap and issue the next Manufacturing R&D solicitation in July 2010.

7. Panel 3: U.S. Manufacturing Needs

The workshop concluded with a panel discussion on U.S. SSL manufacturing equipment and infrastructure needs. "We'd like to see a significant role for SSL manufacturing in the United States," said moderator Brodrick. "Do we have the right people with the right talent? What can industry do to develop the right infrastructure? What's the proper level of automation?"

Chuck Berghoff of OptoElectronix kicked off the panel discussion with an examination of U.S. SSL manufacturing strategic considerations and issues. "We really have an opportunity here to create new companies, new businesses, new jobs, and a new industry," he said. Berghoff made the point that although today's supply chain is global, the labor rate is a small component (3–5 percent) of the end cost on a high-power solid-state light engine. He cited automation as a key to cost and quality control, and called for more standardization of components and subsystems. Berghoff also emphasized the importance of infrastructure as well as a good education system.

Tom Morrow of SEMI, the global association for the microelectronics supply chain, presented a snapshot of worldwide LED fabrication capacity, noting that the vast majority of facilities are in Asia but that half of the equipment and materials that support them are in the U.S. He said this is the way the U.S. can play a key role in SSL manufacturing — i.e., by supplying equipment and materials. "Equipment and materials companies in the United States are going to be critical enablers of the worldwide challenge of reducing fossil fuel usage," Morrow stated. He cited manufacturing cost reductions as being more significant for SSL at this point than efficiency improvements.



Dedicated LED manufacturing facilities worldwide

Mike Peanasky of Bridgelux discussed the challenges facing SSL manufacturers, approaching the subject from the point of view of a smaller company trying to break into large-scale production. He characterized the present state of LED manufacturing as "quite primitive," stating that fabrication isn't well automated and that LED manufacturers face a lot of performance issues that are primarily materials-driven. Peanasky emphasized the importance of reducing the cost of the chip, and identified the lack of design rules for equipment suppliers as another major barrier. Noting the "huge capital costs" involved in SSL manufacturing, he cited a lack of government incentives in the U.S. compared with some Asian countries.

Bill Quinn of Veeco Instruments drew a comparison between radiofrequency power modules and InGaN LEDs. He reviewed the similarities in the two technologies, (e.g., both are compound semiconductors), as well as the differences, (e.g., because the early uses of radiofrequency power modules were by the U.S. military, all the manufacturers got their start with the help of government funding). Quinn observed that for radiofrequency power modules, the chip manufacturing has remained in the U.S., which he attributed in large part to the fact that radiofrequency design, unlike SSL design, is taught in U.S. universities.

Gopalan Rajeswaran of Moser Baer focused on new industry creation and the role of infrastructure, specifically for OLED technology, and described a DOE-funded R&D project his company is undertaking in collaboration with Universal Display Corporation to set up a pilot OLED manufacturing facility in the U.S. He advocated creating product awareness among consumers; establishing standards for product specifications and compliance; fostering the infrastructure through focused R&D, industry-government and intra-industry cooperation, and a robust materials supply chain; and offering financial incentives to offset upfront industry investments.

Question and Answer Session
In the Q&A session, one attendee asked whether there's been any thought about the use of large-scale integration or very large-scale integration technologies embedded in chips rather than using standalone LEDs. Quinn replied that it's difficult to do that because of thermal budgets. Another attendee asked about the best approach for getting the U.S. government to "level the playing field" by providing incentives for SSL manufacturing, the way some other countries do. Morrow's reply was that the playing field is already level; the problem is that "we're just not playing in the United States." He said what's needed right now is education, perhaps followed later on by a mix of tax incentives and rebates.

8. Conclusion

Brodrick concluded the two-day workshop by thanking participants for their input and participation. He noted an additional DOE SSL workshop in 2010 — the SSL Market Introduction Workshop in July — and also encouraged attendees to stay apprised of DOE SSL program activities by visiting www.ssl.energy.gov.

Workshop presentations and materials referenced in this report can be found at http://www1.eere.energy.gov/buildings/ssl/past_conferences.html.

APPENDIX: 2010 SSL Manufacturing R&D Workshop Participants

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