Solid State Lighting OLED Manufacturing Roundtable Summary

Introduction

On March 14, 2013, eleven OLED experts gathered in Washington, D.C., at the invitation of the Department of Energy (DOE) to help identify high-impact task areas for the Manufacturing Research and Development (R&D) Initiative. Participants were asked to give brief presentations addressing several discussion points of their choosing that were distributed prior to the roundtable meeting. These discussion questions, listed below, relate to the barriers and opportunities associated with the current state of OLED manufacturing, as well as how DOE can best facilitate progress within the industry.

1. To realize the full energy savings potential envisioned by the DOE SSL program, the supply of SSL products will need to expand by orders of magnitude. In terms of light output, they need to grow from providing a very small percentage in 2012 to 1500 Tlm-hrs by 2025, just for the residential sector. By that time, almost half the electric light in the US should be coming from SSL sources; globally it may be more. That suggests that fundamentally new manufacturing methods and processes will be needed very soon to get the ball rolling! What needs to be done? Who does what? How does DOE help? Can this need be met?
2. What innovation(s) could lead to a step change in SSL performance, cost and deployment?
3. Are existing test procedures and equipment suitable for high volume production? What changes are needed? How can we reduce the cost of testing? What can DOE do to facilitate it?
4. Where are the weaknesses in the manufacturing supply chain? How might we address them?
5. How can DOE best assist manufacturers of materials, components, and equipment?
6. Are there specific common problems where a collaborative approach might be most effective?
7. Where will OLED manufacturing be four years from now? Will there be a dominant manufacturing process and materials set? Can we describe it? Is it important? If so, what do we need to do now to make it happen?
8. Should we abandon the goal of setting up an OLED pilot line in the US? If not, who will take the lead and how best can DOE help bring the community together to support such an initiative?
9. How can the DOE SSL Program best help to facilitate development of advanced manufacturing for SSL? Are solicitations and individual projects the right path? In what areas of manufacturing, generally, is DOE likely to have the biggest impact? Are there projects that could have a dramatic and rapid impact?

Participants were also asked to comment on the organization and content of the Manufacturing Roadmap.

This report summarizes the discussions of the roundtable meeting, including the tasks framed in the Manufacturing Roadmap, a summary of discussion points relevant to those tasks, and an outline of participant presentations and remarks.

Discussion of Questions

Participants of the roundtable provided short presentations as outlined below in response to the discussion questions.

Question 1
To realize the full energy savings potential envisioned by the DOE SSL program, the supply of SSL products will need to expand by orders of magnitude. In terms of light output, they need to grow from providing a very small percentage in 2012 to 1500 Tlm-hrs by 2025, just for the residential sector. By that time, almost half the electric light in the US should be coming from SSL sources; globally it may be more. That suggests that fundamentally new manufacturing methods and processes will be needed very soon to get the ball rolling! What needs to be done? Who does what? How does DOE help? Can this need be met?

Michael Hack, Universal Display Corporation

- DOE should continue to subsidize pilot production (broadly, including manufacturers of all components) or provide loan guarantees to supplement private investment.
    - This is important because it encourages the development of commercial products and reduces the financial risk of early low-volume production for panel and equipment makers.
- DOE should place more emphasis on OLED lighting demonstrations because these will help raise consumer awareness of OLED lighting. In turn, this will encourage adoption and grow the market.
- DOE could provide or encourage usage subsidies for OLED products.
- DOE should place more emphasis on energy conservation, as opposed to generation.
    - The SSL Program has expended $250 million, while 4 gigawatts of energy have been conserved (same energy savings as generated by solar for $13 billion spent).

General Discussion

- Increasing adoption and awareness of OLED lighting:
    - Getting energy-efficient lighting, like OLEDs, into LEED building either renovations or new construction. This would be easier than breaking into the commercial market.
    - As far as getting OLED products into new construction, there is a timeline. The commercial market has a fairly long cycle; production and installation in the building takes years.
    - Another avenue could be implementation in government buildings because they are theoretically more willing to accept energy-efficient products.
    - Lighting Facts is another good way to spread OLED awareness. There is no administrative barrier to getting the products listed in the Lighting Facts database. In addition, consumers are educated to the point that they are using Lighting Facts to find acceptable products.
    - GATEWAY, which frequently demonstrates prototypes or small-scale production, would also be very receptive to showcasing OLEDs if they are available.

Question 2
What innovation(s) could lead to a step change in SSL performance, cost and deployment?

John Hamer, OLEDWorks

- There is not a supply problem (as implied in Question 1); there is a cost problem. In order to achieve the 2015 direct cost targets (roadmap table 3.3), it is important to continue focusing on reducing cost.
- There are three major opportunities to drive down cost:
    - Cost-effective substrate with built in anodes and light extraction.
        - Cost effective substrates with light extraction $28/m^2.
        - Extracting 70% of light generated.
        - Anode sheet resistance <30 ohms/sq.
        - Meet cost targets of $60, $44, $28 per m^2 of good product (after 80% yield and 80% glass pattern usage) in 2015, 2017, and 2020, respectively.
    - Cost-effective (thin-film) encapsulation solutions.
        - Cost effective encapsulation solutions $17/m^2.
        - 20-year shelf life without dark spots >100 microns.
        - Meet cost targets of $35, $24, $17 per m^2 of good product (after 80% yield and 80% glass pattern usage) in 2015, 2017, and 2020, respectively.
    - Cost of equipment for whole line.
        - Equipment with capital cost to throughput ratio of less than 100:1 $/m^2/year of good product.
- The industry needs the ability to produce in increasing volumes as market demand grows which means continued focus on manufacturing technology and the cost of goods sold (not just the BOM).
    - Should focus on delivering the needed technology to achieve the 2017 and 2020 cost goals in table 3.3 of the Roadmap.

General Discussion

- Performance areas that need to be stepped up include efficacy and lifetime.
- First existing high volume processes need to be identified and then high performance products should be developed from those processes.
    - Trying to refine a high cost process to a low cost one is difficult so funding priorities should include proposals that are outside the box in this sense.
- High volume scaling or scaled production, whatever drives down per unit costs or costs in general, is important. Scaling approach and process considerations:
    - Coupling the materials performance and the viability of putting the materials together to produce a product. One challenge with scaling is sources. Evaporation sources are typically used with solution processing for some layers.
    - Throughput and process control are challenges. Take advantage of lowering per unit costs via higher throughput; eliminate redundant steps like characterization.
    - Total investment is also a problem when trying to reduce per unit costs. There is a capital expenditure (CAPEX) barrier to entry. The biggest issue surrounding this is convincing potential investors when similar LED products already exist on the market.
- It is not possible to reach low per unit costs if CAPEX barriers are too high for entry. This could be a possible area for DOE assistance
    - Or DOE could help reducing cost at lower volumes instead of reducing the CAPEX. This could be an interim level of assistance for the DOE.

Step change vs. incremental improvements:

- To break out of niche markets and achieve big profits OLEDs need high volume and low cost manufacturing. However inevitably in the beginning the OLED industry will be working at low volumes because those niche products are what will allow for market entry. So what is truly needed is a door-way (niche market) and a pathway (high volume/big market) for OLED success.
    - OLEDs need a niche market now otherwise they cannot compete due to insurmountable costs. The current focus should be on small incremental improvements and setting more near-term goals.
    - Establishing a niche market is important for the development of OLED lighting but to achieve the energy savings goals set by DOE the track to general lighting must also be kept in mind.
        - Niche markets can make for good business but they do not allow for meeting the DOE's goals. And furthermore DOE will not provide assistance unless the end game shows OLEDs achieving energy saving goals. From a DOE standpoint there has to be a pathway to scale to energy efficiency. And this does not mean there has to be a goal set at the outset but there does have to be some pathway to the target in mind.

Question 3
Are existing test procedures and equipment suitable for high volume production? What changes are needed? How can we reduce the cost of testing? What can DOE do to facilitate it?

<u>General Discussion</u>

- Can an LM-79 test be conducted on a large OLED luminaire? How should lumen maintenance test be conducted on OLEDs? If OLEDs are going to be large in size, perhaps another method to characterize them should be devised.
    - It is worth considering this now as these tests will need to be performed on all products.
- Are there sufficient equipment and processes for testing within the overall manufacturing process?
    - From a component supplier standpoint, there needs to be a test method for light extraction. It must fall between the glass supplier and the original equipment manufacturer (OEM); otherwise it can lead to very expensive fallout.
    - Equipment and processes used to qualify the products before they reach the customers are sufficient.
        - Once a large enough manufacturing volume is attained, there is a maturity in the supply chain between the supplier and the customer, which enables specification of acceptable variation in the downstream production processes.
        - This is an area in which OLED lighting can benefit from OLED display. The OLED display industry has official procedures in order and the OLED material supply chain is getting more mature now.
- Is there a means to test deposition processes?
    - OLED panels have a lot of variables and failure modes, and research is needed to spot particulates that cause failure.
        - Panel inspection has been well developed in the semiconductor industry, but there is not a good automated tool for panel inspection.
    - Another participant commented that there are two main area of manufacturing testing: process testing and qualification of product. The former is more important and the industry does not have everything needed to do it well.
        - There are no standard OLED testing methods. As far as in-process testing, being able to cost-effectively measure and control the deposition process vacuum

levels, cleanliness, etc.) is important. Affordable tools are not available which presents an even greater challenge in attaining the goal of a 2x cost reduction.

Question 4
Where are the weaknesses in the manufacturing supply chain? How might we address them?

This topic was addressed in combination with Question 5

Question 5
How can DOE best assist manufacturers of materials, components, and equipment?

Tom Trovato, Trovato Mfg., Inc.

- Government should be an incubator and should not inhibit small businesses.
- DOE should recognize the concerns and needs of small business growth and consider those needs when creating funding opportunities.

Hongmei Zhang, Plextronics

- Performance-wise, OLED lighting is on track to achieve near-term future market goals. However OLED lighting will not succeed in the mass-market arena unless manufacturing costs can be reduced.
    - If these costs do not come down, OLED lighting applications will not even survive in niche markets.
- Focus needs to be on reducing costs through process development.
    - Economy of scales and experience curves are two important factors to achieve cost reduction. These factors are both highly dependent on investment in capacity. Economies of scale do not make sense for OELDs currently because investment requirements are too high.
    - However, costs can also be reduced through new process improvements that lead to better manufacturing yields more than in materials cost reductions.
        - Poor yield is one of the reasons that OLEDs have not been able to come down on the cost curve, apart from material costs.
        - The general problem that OLEDs have with low production is that yields get worse as panel sizes increase. One small defect can “fail” an entire panel by causing the panel to short.
        - Cost-effective processes for defect passivation or reduction layer at the anode need to be developed.
    - Material costs are high. There is not a lot of information on costs of other processes such as lithography, anode structure processes, gird and patterning. These processes can waste a lot of material and add significantly to the overall cost.
        - Effort should be put into moving towards an additive process (direct patterning) in order to reduce material costs and increase throughput.
- DOE can assist manufacturing efforts in the following ways:
    - Playing a more active role in encouraging collaboration on common problems like materials and equipment.
    - Funding programs that focus on manufacturing process development to improve yield or reduce the number of process steps for cost reduction.
    - Giving priority to material and process development that can be incrementally scaled up from lab scale to low volume production in the near term without significant capacity investment.

David Collins, Kurt J. Lesker Company

- DOE can help manufacturers by funding continued research on materials and deposition sources.
- There are still fundamental issues with material costs and source utilization and suitability for large area use need.
    - Uniformity of large substrates is becoming more and more of an issue.
    - There is uncertainty as to whether the industry can scale up existing technology to larger areas. Better sources must be developed and therefore funding should be directed to source development projects and possibly even collaboration with academia will be necessary.
    - Speeding up production, instead of increasing panel size was suggested. Shared results and shared structures are a means to this end but would require further collaboration similar to SEMITECH to unify efforts. If the industry collaborates, shared technology and device structures will allow production to speed up.
        - This collaborative resource-pooling will be able to get products to market faster than scaling to larger panels.
        - Fast small-panel production will reduce costs for luminaire makers. Luminaire makers will need to adjust.
- Currently the industry works with complex device structure; there are no standard structures. This is an area the DOE could help the industry with by supporting standardization.
- Encapsulation still remains a weak link for the industry and needs further development.

Dennis O'Shaughnessy, PPG Industries, Inc.

- DOE can support manufacturers in two key ways:
    - Fund projects for low cost, high performance, scalable technologies.
    - Set goals for necessary performance and scale.

General Discussion

- On the topic of scaling:
    - Simply scaling the system is not the objective; the display industry has already done this. The OLED lighting industry needs to focus more on smaller innovations instead of just following the display route of large scaling equipment.
        - In lighting it is not necessary to be concerned with high resolution issues like the display industry.
    - Another line of thinking to first focus on faster production of smaller sized panels before tackling larger sizes. In this way, luminaire manufacturers will not need to adjust the design of their luminaires. Other benefits of the 'small and fast' route are:
        - It will help OLED success in the niche market which is an important step.
        - It provides stepping stones or segues for the industry from 'small and fast' to 'large and fast'.
    - Pursuing the 'small and fast' method raises the question of why are OLEDs needed at all if point sources (LEDs) already exist and can do this. Is there enough distinction between from LEDs when OLEDs follow the 'small and fast' route?

Question 6
Are there specific common problems where a collaborative approach might be most effective?

<u>David Maikowski, Guardian Industries Corp.</u>

- Glass substrate specifications/requirements present an opportunity for a collaborative approach.
  - OLED lighting would benefit from collaboration between flat glass and OEMs in developing a baseline specification for glass substrates that would balance both manufacturing cost and performance needs.
    - Specification should include thickness ranges, tolerances, surface roughness/defects, in-body defects, etc.
- Low-cost electrode development is another opportunity area.
  - ITO (vacuum sputter deposition) is the current material of choice for the anode plate's electrode, but it is a very expensive material (~18% of BOM).
    - This cost is typically justified and absorbed in high-volume markets such as consumer electronics (capacitive touch).
  - A key opportunity exists to address the cost structure of OLED lighting by developing more cost-effective materials and deposition processes to replace ITO and forge better alignment with the cost, performance, and volume of the market.
    - This will require collaborative material research and rapid prototyping with OEM partners for production validation and qualification.
- Light extraction represents the third identified area that would benefit from collaborative action.
  - This is a key priority in attaining the performance goals for OLED lighting. It will require close collaboration between glass and OLED OEMs to realize manufacturing capability in this area. Two of the hurdles involved are:
    - Optical band gap considerations between the light extraction layer and the organic layers being used.
    - Rapid prototyping and manufacturing volume test runs which will be required to validate improvements in performance and costs (materials and process) for full-scale production manufacturing.

<u>General Discussion</u>

- From a manufacturing standpoint, substrates and encapsulation are the most important areas for collaboration.
  - One specific area for collaboration in the substrate arena was the reduction of raw materials. It was indicated that glass substrates are necessary in order to reduce costs. However, several questions must be answered first:
    - What is standard glass,
    - How can it be made to work as a substrate, and;
    - How can cost and defect level be balanced?
  - Glass can work in this capacity if light extraction and the deposition layer are not constricted by its use.
- Extraction efficiency was also noted as a problem area OLEDs currently face.
  - Some participants stressed that extraction efficiency must be increased at least two-fold for any new products.
  - Others though that it is more important to focus on the percentage of light output rather than talking about x-fold improvements. This metric is a better basis for comparison; otherwise it is just a comparison of one (entity's) multiplier to another.
    - What is the necessary photon output? What percent of photons? 70%?
  - The idea was proposed to form a group whose purpose would be discussing these requirements and developing potential solutions.

        - It was noted that if this group were to be formed discussion must stay within parameters of manufacturing (e.g., what are the best ways to integrate substrates or extraction layers) and not veer into the R&D realm (e.g., designing a new light output method).
- Material suppliers view panel design or panel layout as a key area for collaboration because as a material supplier it is important to be aware of how the stack is built and (thus) how to integrate the components.
    - Currently, the common or standard panel design incorporates a serial connection.
- The OLED lighting industry could collaborate with the Arizona (ASU) Flexible Display Center with the objective being to achieve the DOE cost targets for OLED lighting.
- OLED lighting can also collaborate with equipment manufacturers, although there would be non-compete issues.

Question 7
Where will OLED manufacturing be four years from now? Will there be a dominant manufacturing process and materials set? Can we describe it? Is it important? If so, what do we need to do now to make it happen?

David Newman, Moser Baer Technologies Inc.

- Substrate costs are the biggest cost structure challenge. The high costs of integrated substrates make it seemingly impossible to achieve overall manufacturing costs in the range of the stated DOE target.
    - Current cost is thousands of dollars per square meter and the target for 2015 is $52/m^2.
    - Meeting a $250/m^2 overall manufacturing cost target for OLED lighting products is not attainable if the integrated substrate alone costs more than $1000/m^2.
- Integrated substrates must include internal and external light extraction layers, patterned TCO, grids, and insulating layers, and the entire substrate cost structure must be less than $50/m^2.
    - Without a path to commercial volumes of integrated substrates, OLED lighting products will remain too expensive to capture volume and will remain suitable only for niche applications.
        - Reducing encapsulation costs are also important. Currently, glass is used for encapsulation which works but is expensive. However, substrate costs are the biggest financial challenge.
    - A few key companies are developing their own integrated substrates, but they have not yet reached mature enough levels for a pilot line.
    - Most of the current programs only address a partial problem set which is an issue when the target is if the integrated substrates cost structure is to fall within the $50/m^2 target.
- Companies with pilot lines currently cannot acquire substrates at a cost that allows increased production capacity.
    - These lines are going to be based on small substrates which can be scaled somewhat but not to very large sizes in the long run.
    - In the current and near-future time frame equipment necessary to produce larger products will not be affordable.
- Scaling up requires equipment and equipment requires capital. Creating integrated substrates helps reduce the cost right now.
- MBT is in the development stages of a pilot line, with an initial focus on small form factor, fast throughput, and product-size production. The production cell is designed so capacity can scale with market growth. Under this modular approach, scaling up would be more manageable as capacity additions would only require replication of a production cell instead of a total

restructuring. However, until integrated substrates at cost structures under \$50/m^2 are developed this venture will not be profitable enough to commence production of OLED lighting products.
  - In order for this concept to be economically viable, equipment and integrated substrate costs need to decrease. The current cost structure makes it difficult for companies to justify investment.

David Maikowski, Guardian Industries Corp.

- The near-term future of OLED lighting rests with the major international players.
  - They currently have manufacturing investments and assets in place to bring commercial products (although not economically-viable) to market.
  - In the next five years, one of these companies will bring OLED lighting into non-niche general lighting markets to capture the forecasted market demand rise beginning in 2016.
- It will be crucial for the U.S. to ensure an OLED lighting OEM to service low-volume niche lighting applications to avoid a complete reliance on imported technology.
  - Projects that promote a U.S. manufacturing base should be funded.
  - The problem is not the performance but rather the dilemma between cost, performance and volume.
- Standard glass has to be compatible with the OLED. The industry needs to make standard glass fit as a standard substrate, not a borosilicate/display-grade glass.
  - Incorporation of light extraction layers is also important, so to some extent the roughness of the glass might not be as crucial with the addition of these layers.
  - Guardian has been collaborating with a European company to develop a 15Ω ITO with 95% yield.

Michael Hack, Universal Display Corporation

- Four years from now, OLED manufacturing will be geographically distributed across all three continents: Asia, Europe, and hopefully, with support, the U.S.
  - This is an area where OLEDs differ from LEDs.
- Promotion and support is critical to break out of the current "low-volume, high-cost" cycle to take OLED lighting to the next level.
  - The lighting industry can learn lessons from the display industry.
  - OLED displays are successful today because they were championed by Samsung. Samsung electronics and Samsung display were bitter rivals. They have driven that industry.
- Momentum is very much focused on vacuum thermal evaporating (VTE), thus in 2017, VTE will still dominate manufacturing production. Flexible panels will start to become important due to the OLED display industry and for differentiation from current products.
  - Once there are flexible displays it will be easier to transfer the technology over to OLED lighting, which will have a big impact.
    - The display industry is approaching to 'Gen 8' manufacturing lines.
    - The production techniques used for OLED lighting and display will be the same.
- It is unclear how much any specific OLED process truly determines overall product cost.
  - Depreciation and substrate system costs are heavily driven by volume.

David Gotthold, Pacific Northwest National Laboratory

- The industry needs to recognize traditional market acceptance paths.
  - Need to enable building from small to large markets; it is not possible to start at the large market. LEDs had years of development before they entered the general lighting market.

        - The Roadmap should align with this concept by incorporating intermediate targets. It should be recognized that there are intermediate steps on the path to high volume.
- It is also important to the identify barriers to small volume and focus efforts on overcoming them.
    - Materials, substrates and capital are several of the barriers.
        - Need solutions to reduce capital costs for deposition to less than $100/m^2/yr.
        - The case is similar for substrates. Float lines do not make sense until production reaches costs in the hundreds per square meter range.
        - To ensure good use of capital, process and yield improvements are needed.
    - DOE can help focus on what are the barriers to small volume manufacturing.
- In four years, there should be a range of stacks, structures and devices to address appropriate markets. There is no one device stack, material set, or substrate; these need to be kept flexible to cater to various markets.
    - Presently, it does not make sense to focus on defining a stack structure because different companies will be at different points on the device complexity curve.
    - Stack structure has to remain flexible as there will be tradeoffs between cost, performance, and yield.
        - Device complexity improves performance but will hurt yield.
        - Flexible vs. planar substrates.
        - High performance materials can have shorter lifetimes.
    - Complexity rises very fast over time and as volume and scaling come into play structures can be simplified. Once the yield increased so does volume allowing manufacturers to concentrate more on high performance materials.

<u>Drew Hanser, Veeco Instruments, Inc.</u>

- OLEDs need a compelling value proposition beyond energy efficiency in order to succeed in a market with LEDs.
    - Market observation: LED and OLED products will coexist. OLEDs are characterized as low-harshness area source lighting while LEDs are point sources.
        - However, LEDs are moving into area source lighting.
    - Energy efficient lighting already exists with LEDs. LEDs are more incumbent that OLEDs therefore it is necessary to devise another value proposition to entice consumers to select OLEDs over LEDs.
- OLEDs are currently in the market entry phase; consumers are excited about the products out there but there are a number of barriers present in the niche market. Volumes will increase as manufacturing costs decrease. This will be an important and needed transition to the market-traction and production-scaling phase.
- In order to retain that momentum and enable market growth, performance and manufacturing improvements are necessary (i.e., there are performance and equipment requirements that must be met), especially in the following areas:
    - Performance (lm/m^2).
        - Increase panel performance by increasing light output per unit area.
        - Largely dictated by materials and device structure.
    - Manufacturing cost ($/m^2).
        - Decrease overall manufacturing cost by decreasing cost per unit area.
        - Decreasing manufacturing costs are crucial to enabling market growth.
    - Panel cost ($/klm). The combined outcome of the previous two metrics is $/klm.
        - Performance and manufacturing costs should be tracked together.
        - Focus on depreciation and labor costs; both of which will require significant advancements.

- To successfully reduce manufacturing costs, three primary challenges must be overcome:
    - Substrate size.
        - Transition from Gen 2/2.5 to Gen 5.5 to reduce depreciation cost per unit and reduce overall cost – lowest per unit cost based on CAPEX.
        - There is much to be gained by moving to economies of scale and supporting larger sized panels because the throughput achieved is accomplished at the lowest per unit cost.
    - High throughput.
        - High-performance solution processes, high output thermal evaporation sources, and encapsulation developments are needed to enable shorter TACT time on large area substrates and reduce manufacturing costs.
        - There are solution processes as well and encapsulation could have the ability for deposited approaches.
    - High yield.
        - Need optimized equipment and processes to improve uniformity and yield which will have a significant impact on cost.
- Solution manufacturing processes:
    - Have a performance gap compared to evaporation processes.
    - Challenged to provide a process for the entire device stack.
- DOE focus should be on developing a strategy to accelerate low-cost commercialization via the following methods:
    - Fund key manufacturing enablers like Gen 5.5 and high output thermal evaporation.
    - Encourage collaboration between members of the OLED supply chain.
    - Rapid prototype pilot production to reduce testing barriers for new process equipment.
        - Use established lines along with new sources, new materials, and new encapsulation modules to reduce these testing barriers.

<u>General Discussion</u>

- It is better to focus on solution processing instead of evaporation processes because it can result in lower cost and higher throughput as well as improved scalability. However, evaporation methods are still better in terms of performance and it is very difficult to develop a solution process for an entire stack, though hybrid structures are more easily obtained.
- The key manufacturing enablers for cost effective manufacturing:
    - Larger size substrates, high output thermal evaporation processes Encourage collaboration. Need pilot lines to incorporate material, process and equipment developers to get the best overall process possible.
    - Rapid prototyping will reduce the barrier to testing new process equipment which is a big opportunity area for advancements.
- How can U.S. equipment manufacturers compete with companies already making OLED deposition equipment for large area panels? Should a joint venture be considered?
    - To become competitive, significantly reducing TACT time for these types of systems is crucial.
    - From an equipment manufacturer's perspective, it is challenging to determine how to get the technology into the end user's hand and determine whether there is a market for it. The display industry has well-defined needs, and Veeco is leveraging display developments into light applications.
    - Reducing CAPEX is a problem. Partitioning or sizing the line is an important consideration in doing so.
    - Evaporator source technology developed for the display industry can be applied directly to lighting. In this respect, lighting is a market without significant development costs.

    - A participant doubted that the $10/klm target can be met with Gen 5.5 equipment, and Gen 8 may be needed. If the target was within the $20-25/klm range, Gen 5.5 would be adequate.
- On the topic of VTE dominating manufacturing production:
    - The display industry claims they are transitioning to solution processing in 2015 but the big industry players are already heavily investing in Gen 8 VTE equipment.
    - Flexible panels will become an important product. Once the display industry launches flexible OLED displays it will be easier to transfer this technology to OLED lighting which will serve as a differentiating attribute from LEDs.
        - This should have a big impact as early as 2017.

Question 8
Should we abandon the goal of setting up an OLED pilot line in the US? If not, who will take the lead and how best can DOE help bring the community together to support such an initiative?

<u>Dennis O’Shaughnessy, PPG Industries, Inc.</u>

- A U.S. pilot line is still a good idea, but the bar for “pilot” keeps moving up (in terms of scale, performance and cost). Since pilot lines require a few years to get started it is necessary to anticipate what characteristics a pilot line will need in the future (e.g., bigger and faster).
- The mission should be a combination of commercial production and using extra line time for new technology development funded by the government. This would help encourage commercial startups by supporting their endeavors before they reach full capacity.
- IP should be shared by a consortium. IP will always be present in these situations, and will need to be negotiated with every interaction.
    - Roundtables and workshops have been very successful at encouraging collaboration by providing a way for industry groups across the value chain to share perspectives.
- Currently, there are only two U.S. panel manufacturers. One option could be to encourage foreign companies to build big facilities in the U.S. and take vested management of suppliers. The other option is to supply from within the U.S.
    - More interaction with the developing global market is needed to make progress towards the mutual goal – producing more lumens at high efficiency (thereby realizing greater savings). The route selected should be the one that will ultimately lead to producing the most high efficiency lumens in the U.S.

<u>David Collins, Kurt J. Lesker Company</u>

- DOE should not abandon the goal of a U.S. pilot line.
- This initiative can be supported by forming a consortium of equipment manufacturers, academia, and potential device manufacturers that can take the lead by defining standards and test criteria (e.g., SEMATECH).
- Developing joint research and development projects between industry and academia along with open sharing of technology would help move the industry towards the development of a U.S. pilot line.
    - DOE can fund and monitor research and disseminate information.

<u>Michael Hack, Universal Display Corporation</u>

- DOE should not abandon a US pilot line. Pilot lines are important for building momentum and infrastructure for future profitable business.
    - A key difference between lighting and display is that the former is much more local. Therefore, it is important to have the manufacturing base local as well.
- DOE could help bring the community together to set standards and test procedures, etc. to

accelerate industry growth.

- DOE could also support luminaire makers to use U.S. output and sell OLED products.

John Hamer, OLEDWorks

- DOE should support a pilot line in the U.S.
- OLEDWorks has made progress in its pilot line:
  - Designed, built, installed, started, and debugged an OLED lighting panel production line in Rochester, NY.
  - Currently transitioning product formulations from research to production lines.
  - Sales from mass production will start this year.
- The facility has attracted many companies interested in collaboration for developing technology for OLED lighting.
  - Most are U.S. companies.
- Lighting is different than the display industry and the U.S. can compete.
  - Lighting is diverse. There are thousands of luminaire makers, whereas there are only a few phone/tablet/TV makers.
  - Lighting is about design, decoration, and fashion.
  - OLED panels are a visible part of the luminaire and therefore part of the design. This contrasts with other light engines, such as fluorescent, incandescent, HID, LED, which are hidden in the luminaire.
  - There is a big opportunity to distinguish products in the market through design.
    - There is demand for custom sizes, shapes, colors, features
    - There is demand for responsive suppliers – fast, flexible, local, partnership between panel supplier and luminaire maker

General Discussion

- The ruling opinion among participants was that the goal of setting up and OLED pilot line in the U.S. should not be abandoned.
  - The industry can learn a lot from pilot lines that already exist.
- Consider revising product development support programs; manufacturing without a product is unproductive.

Question 9
How can the DOE SSL Program best help to facilitate development of advanced manufacturing for SSL? Are solicitations and individual projects the right path? In what areas of manufacturing, generally, is DOE likely to have the biggest impact? Are there projects that could have a dramatic and rapid impact?

Dennis O'Shaughnessy, PPG Industries, Inc.

- DOE should fund projects for low cost, high performance, scalable technology. Projects with innovative approaches in particular deserve attention.
- Another way the DOE could support the industry is helping to identify a target market that will adopt products early for demonstration (e.g., legislate efficiency in government-owned new construction and renovation).
- Funded projects should be those that have the potential to have a dramatic, rapid impact. Suggested project areas:
  - Low capital cost/large-scale organic deposition.
  - Low-cost/large-scale materials and components processes.
  - DOE/EERE/Building Technology Office should take an integrated approach, as well as facilitating the development of the technology.

        - Promote/implement codes for lighting efficiency.
        - Integrate efficient lighting with other new building technologies (e.g. enhanced day-lighting, switchable glazing and control systems).
        - Grand challenge for "Net-Zero Energy Buildings" to reward energy efficiency.
        - Energy Efficiency Buildings Hub.
        - Define the market beyond niche, specialty products.

<u>General Discussion</u>

- The overall FOA process needs improvement:
    - There is a big delay between when an FAO begins and when it receives funding. By the time research starts, ideas are old and competition has moved on.
    - The time period has recently been shortened from one year to nine months and the DOE is looking to shorten this to six months in the next year.
        - This process must move faster so work can be performed on good ideas within three months of the FOA.
        - A participant suggested reducing this time to three months is what is needed.
    - DOE should issue FOAs more frequently – every four months, use letter-of-intent to reduce work for all, and encourage more high-risk, high-rewards process technology development for OLED lighting.
    - FOAs should encourage more high-risk, high-reward process technology developments and use smaller awards to seed early work.
- DOE can help support the industry through developments of and improvements in standards and testing.

Manufacturing Task Notes

The following tables provide descriptions, metrics and goals for the discussed tasks. The task tables shown do not reflect any modifications suggested by roundtable participants. All comments, including suggested changes to each task, are summarized below each of the respective task tables. These comments represent a summarized transcript of the general commentary at the roundtables and require further discussion at the 2013 DOE Solid-State Lighting Manufacturing R&D Workshop on June 5^{th} and 6^{th} in Boston, MA. The combined results of the Roundtable and Workshop discussions will guide the DOE in soliciting projects for the OLED Manufacturing R&D Program.

M.O1 OLED Deposition Equipment	
Support for the development of manufacturing equipment enabling high speed, low cost, and uniform deposition of state of the art OLED structures and layers. This includes the development of new tool platforms or the adaptation of existing equipment to better address the requirements of OLED lighting products. Tools under this task should be used to manufacture integrated substrates or the OLED stack and must demonstrate the ability to maintain state of the art performance. Proposals must include a cost-of-ownership analysis and a comparison with existing tools available from foreign sources.	
Metric(s)	**2015 Target(s)**
Initial Capital Cost/Line Capacity	$100/m^2
Minimum Substrate Size	10x10cm (may be batch-processed)
Area Utilization	>80%
Uptime of Machine	>80%
Thin Film Layer Yield	>95% per layer (80% overall)
Materials Utilization	> 70%

M.O1 Roundtable Participant Comments

- This task should emphasize the need for step-function innovation, beyond simple scaling or incremental improvement. DOEs should only fund significant innovations; let the display industry work on incremental improvements.
    - Project proposals should make a compelling case for how their tool is unique and a significant improvement over existing equipment.
        - A particularly valuable innovation would be a method to reduce upfront cost while maintaining reasonable throughput.
- Adding a metric for total capital cost was suggested in order to direct focus on absolute value (as opposed to scaling).
    - While a reasonable range for the capital cost target was not established, attendees maintained that an aggressive target (such as a $10M tool) would be an unrealistic starting point, suggesting a higher target ($20M or <$25M) instead.
    - It was also noted that a way to normalize small- and large-scale production (in order to create a baseline for comparison) should be developed before this metric is added.
- Initial Capital Cost/Line Capacity metric
    - Explicitly state that the metric is defined for good product produced in one year (i.e., $100/m^2/year of good product).
        - Inclusion of this statement is important as it directly relates to depreciation.
    - Currently, the industry cost per square meter is around $1,000 - $2,000.
    - The term 'good product' needs to be defined. Community assumptions are thus:
        - Equipment run-time at 80%,

        - 80% of glass is used in panels,
        - 80% of the panels produced are good products.
- Including long term targets *in addition* to short term targets for this task was emphasized. Participants suggested adding a 2020 goal to replace or supplement the 2015 target, allowing DOE to set different interim goals.
    - However, it should be noted (in the description) that projects delivering near-term targets must be able to explain how near-term success will translate to long-term progress. Proposals must meet both the short- and long-term goals.
        - For example, a proposal could include an initial metric with capital and a long term goal with depreciation.
- In addition to initial capital cost, material utilization and minimum substrate size were also mentioned as important metrics for this task while yield, uptime and area utilization are not as essential as they are represented within the capital cost metric.
    - To invite innovation, this task should not be constrained by too many metrics or parameters.
    - The idea is to encourage the development of novel ideas and innovative approaches to meet the requirements. This is more important than addressing equipment specifications.
        - To stress this point, incorporate 'innovative' into the task description.
- There was no definitive consensus on whether M.O1 should be elected as a priority task.
    - It was noted that this task was selected as a priority last year and focused on the stack, not on deposition of layers in the integrated substrate.
- It was recommended that this task should focus on the OLED stack and integrated substrates be taken out of this task and moved to M.O3. It was suggested that a new task be created to focus on encapsulation.
    - Many agreed that the integrated substrate task should not just produce an anode or light extraction solution, because a complete substrate solution is needed by manufacturers.

<table>
<tr><th colspan="3">M.O2 Manufacturing Processes and Yield Improvement</th></tr>
<tr><td colspan="3">Develop manufacturing processes to improve quality and yield and reduce the cost of the OLED products. Manufacturing tolerances should be defined to ensure the desired control over product performance. These process windows should be maintained over the whole substrate and be reproducible panel-to-panel.</td></tr>
<tr><th colspan="2">Metric(s)</th><th>2015 Target(s)</th></tr>
<tr><td>Reliability</td><td>Yield of good product</td><td>80-90%</td></tr>
<tr><td colspan="2">Process cost</td><td>Factor of 2 reduction over current practice</td></tr>
<tr><td colspan="2">Early failures in 1st 500 hour burn in</td><td></td></tr>
<tr><td rowspan="2">Panel to panel reproducibility</td><td>Luminous emittance control</td><td>±10% of nominal value</td></tr>
<tr><td>Color control (SDCM)</td><td>2</td></tr>
</table>

M.O2 Roundtable Participant Comments

- Participants suggested strongly that this task should not be prioritized for the following reasons:
    - It supplies an incremental yield benefit, but it is not the ultimate priority.
    - Funding should be directed to more important areas that provide larger gains.
    - This type of work is easy for the industry to fund internally; therefore, it is not an effective investment for the DOE, which should be involved in higher-risk areas.
    - The nature of this task is more geared towards manufacturing engineering, with the purpose of improving upon an existing process which must be developed first.

M.O3 OLED Substrate and Encapsulation Materials Manufacturing		
Support for the development of advanced manufacturing of low cost integrated substrates and encapsulation materials. Performers or partners should demonstrate a state of the art OLED lighting device using the materials contemplated under this task.		
Metric(s)		**2015 Target(s)**
Substrate	Total cost – dressed substrate	$60/m^2$
	Extraction Efficiency	50%
	Effective Sheet Resistance	< 1 ohms/square
Encapsulation	Permeability of H_2O	10^{-6} g/m^2/day
	Permeability of O_2	10^{-4} cc/m^2/day/atm
	Cost	$35/m^2$

M.O3 Roundtable Participant Comments

- There were several suggestions made for restructuring this task: (1) split into two separate tasks, (2) maintain as is, and (3) combine with M.O1 to create a holistic integrated task.
  - Split this task into separate substrate and encapsulation tasks. Or, carrying this one step further, divide the task into stack, substrate, and encapsulation subsets.
    - There is no advantage to combining substrate and encapsulation into a single task as both are very important.
    - When tasks are split into a manageable set of objectives proposals can be more easily evaluated.
    - One issue with this approach is that too much disaggregation can result in disconnected areas that are impertinent to the whole.
  - Another recommendation was to preserve the task as it stands. It is important, in the manufacturing initiative, that innovations are process-oriented and not product-oriented; the purpose is not to redesign OLEDs.
    - Without a standard OLED stack, it is not feasible to take a top-down (integrated task FOA) approach.
    - It was argued that product and process are different and manufacturing innovation opportunities could be missed by constraining process options to meet certain building blocks.
    - However, others stated that there *are* an established set of building blocks: low-cost substrate, transparent conductor and outcoupling.
  - Finally, it was suggested to list all desired qualities and characteristics from M.O1 and M.O3 merging them into a single task.
    - Proponents of this idea felt that the characteristics and objectives in M.O1 and M.O3 are too interdependent to divorce into separate tasks and that combining them into a single task would invite innovative, holistic solutions.
    - Proposals could specify the addressed qualities with the idea being that proposals can then be segregated based on certain requirements. This way the proposals could address, in a practical way, several pertinent issues.
    - An issue with this approach is that too much task consolidation presents the risk of over-looking certain qualities which could result in an incomplete product.

Encapsulation

- Better and cheaper technologies for thin film encapsulation are needed. Improvements to thin film encapsulation processes are worthwhile to pursue, especially as the industry transitions to this encapsulation method.

- There was discussion on adding an encapsulation lifetime metric and distinguishing between shelf life and lumen depreciation. Including this metric is important because OLED lighting will need a lifetime target to become commercially-viable.
    - LM80 is not applicable to encapsulation failure. What is most likely going to determine OLED lifetime would be failure or permeability of the encapsulation (akin to seal failure in an LED luminaire).
    - It is difficult to capture this lifetime measurement with a metric other than one related to permeability or defects. Regardless, OLED products need to determine a lifetime characterization to be competitive with other lighting technologies in the market.
        - The lifetime metric should cover both shelf life and lumen depreciation.
        - Currently, shelf life testing involves sealing the device in a hot, humid[1] room for 1,000 hours. If dark spots bigger than 100 microns are not present at the end of that time it is assumed the device will have a 10-year shelf life.
- It was argued that the industry is not yet at the point of defining lifetime or failure mechanisms; even the OLED display industry does not have these definitions.
    - While shelf life may represent an appropriate measure or test for encapsulation it cannot define lifetime. However, it can be stated that proposals meet a shelf life requirement per testing conditions described.
- There was discussion on whether 'integrated encapsulation' should be specified in the task description as is done with 'integrated substrate'. The decision was to insert a clause into the description stating that proposals must indicate the encapsulation method and its application.

[1] Room conditions of either: 60°C, 90% RH or 85°C, 85% RH.

M.O4 Back-end Panel Fabrication		
Support for the development of tools and processes for the manufacturing of OLED panels from OLED sheet material. This includes singulation, packaging, testing and repair. The goal is to ensure fabrication of robust OLED panels with consistent color quality, yield, reliability, and lifetime while maintaining a path to low cost. The proposed work should be compatible with the other portions of the OLED manufacturing process and with the creation of OLED panels with state of the art performance and lifetime. The methods used must be able to support the production of different panel sizes and to incorporate electrical connectors that match customer requirements and local regulations.		
Metric(s)		**2015 Target(s)**
Yield	Yield of good panels	90%
Reproducibility	Variation in luminous emittance	±10%
	Color variation Duv	< 0.01
Adaptability	Time to change panel dimensions	< 10 minutes

M.O4 Roundtable Participant Comments

- Participants voiced that this is not the most critical manufacturing issue for the upcoming year and therefore should not be prioritized.
    - Many of the processes related to this task are already addressed or incorporated in other tasks.
- An additional item this task could address is pilot lines which were a topic of frequent discussion. Proposals directed to this initiative could be associated with existing pilot lines. DOE's role could be to facilitate the creation of an advisory board for testing mechanisms related to this task on real (pilot) lines.
    - It is desirable for suppliers to partner with a pilot production line but it is currently cost prohibitive.
        - It is costly to customize materials and pay testing costs for each customer. These expenses discourage collaboration with pilot lines. DOE funding could be devoted to reducing these high risk costs.
        - Although not an appropriate topic for an FOA, another suggested role for the DOE could be to facilitate cooperation and incentivize collaboration between companies.
- In order to incorporate pilot lines in this task, 'pilot line' should be clearly defined to encompass multiple activities and ensure it works for the product.
    - The definition should make it clear that this task would not include R&D systems associated with the pilot line. Pilot lines remove a barrier to commercialization while R&D system advancements only benefit the company.
    - The point at which a pilot line qualifies for reimbursement would also need to be formalized.
    - Additionally, a system for quantifying the reimbursements would need to be determined.

General Roundtable Comments

- Performance and manufacturing improvements required for growth of OLED lighting applications.
    - More work needs to be done beyond just scaling up or acquiring huge machines. Innovation is needed to bring cost down. It is more than just volume (or time) that reduces cost; it is the experience that comes with volume that reduces costs.
    - There is no one device stack, material set or substrate. And similarly, there will always be a trade-off between cost, performance and yield (e.g., device complexity improves performance but negatively affects yield).
    - Reductions in the cost of manufacturing may be the most important challenge facing the OLED lighting industry.
        - Cost reductions would allow for price reductions (without losing profitability) to a level at which mass-market products in residential and commercial lighting applications make sense.

Market Observations

- Lighting is diverse. It is important to distinguish OLED luminaires from other designs in the general lighting market.
    - OLED panels are visible parts of the luminaire design as opposed to other lighting technologies where the light engines are hidden (e.g., fluorescent, HID, incandescent, LED).
- OLEDs and LEDs can coexist with potentially different applications.
    - LEDs as multi-functional point source lighting.
    - OLEDs as low-harshness area source lighting.
- Anticipate slow growth of niche areas for OLEDs.
    - Currently in market entry phase.
    - Volumes will increase as manufacturing costs decrease.
    - Need transition to market traction and production scaling phase.
- Important technical improvements for OLEDs are on track. In the past 3 – 4 years, there is evidence that OLED lighting efficiency is on a growth curve that will progress to the targeted 100 lm/W necessary for OLED lighting to achieve mass-market goals.

OLED Roundtable Participants

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