Solid State Lighting OLED Manufacturing Roundtable Summary

Introduction

On March 9th, 2011 15 OLED experts gathered at the invitation of the DOE to develop proposed priority tasks for the manufacturing R&D initiative. The meeting included a number of "soapbox" presentations from the participants, followed by a general discussion to define specific work needing attention. This report summarizes the conclusions of that meeting, including the proposed tasks, a summary of discussion points relevant to those selections (not all necessarily in support), and a short summary of the soapbox presentations. The next step will be to discuss these suggestions at the SSL Manufacturing Workshop. The resulting document will guide the DOE in selecting funded projects in OLED manufacturing during the coming year.

Proposed Priority Tasks

<table>
<tr><th colspan="3">M.O1 OLED deposition-equipment</th></tr>
<tr><td colspan="3">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. Proposals must include a cost-of-ownership analysis and a comparison with existing tools available from foreign sources.</td></tr>
<tr><th colspan="2">Metric</th><th>2015 Target</th></tr>
<tr><td rowspan="6">Throughput</td><td>Overall</td><td>2015: > 100,000 m^2 per year of good product</td></tr>
<tr><td>Area utilization</td><td>80-90%</td></tr>
<tr><td>Uptime of machine</td><td>80-90%</td></tr>
<tr><td>Speed (web)</td><td>2-10 m/min</td></tr>
<tr><td>Cycle time (sheet)</td><td>≤ 60 s</td></tr>
<tr><td>Yield</td><td>80-95%</td></tr>
<tr><td colspan="2">Cost of Ownership</td><td></td></tr>
<tr><td colspan="2">Materials utilization</td><td>Dry process on sheets: 70-80%
Wet process on web: 90-95%</td></tr>
</table>

Discussion Points

- Throughout the discussion it was stressed that the M.O1 should remain a flexible task that does not limit potential proposals. Participants indicated there is still a great need for innovation and it is unknown which processes and manufacturing methods are best for developing low cost and high performance OLED panels.
- The group felt that patterning should be considered as part of the whole system and not a separate component, and therefore, removed it from the title and description of the task. It was also mentioned that each design and architecture is kept secret and has its own patterning requirements. Perhaps then patterning is not an issue that can be resolved as a group but rather on a case by case basis.
- The task should specify the need for developing integrated substrates (substrate, TCO, internal extraction layer, external extraction layer, barrier). This integrated substrate could include

encapsulation, such as in the case of a plastic substrate.

- Equipment developed under this task should not be solely designed for encapsulation. A tool which combines various layers and that is capable of solving several steps would be much more useful. As the display industry is moving towards inline encapsulation, the lighting industry may be able to piggy back on those processes.
- Though there was discussion on whether DOE should select vacuum thermal evaporation or solution processable deposition as a preferred deposition method, most participants felt that there was not enough information to do so. The participants specified that projects should not be limited to developing solution, evaporation or hybrid deposition methods.
    - Roll-to-roll may not be suitable for the beginning growth phases of the market as the low volumes will not be sufficient to justify the capital expense.
    - Perhaps for the early market phase, DOE should fund a sheet to sheet process or a hybrid solution.
- Many believed that this task should support low volume manufacturing at low cost given the current state of the market and market introduction strategy. Though some mentioned that if the industry does not already have low cost, low throughput equipment earlier than 2015, it is in trouble. This task should focus on what the needs in 2015 (the project end date) will be.
- Several approaches to tool development were discussed:
    - Flexible tools are being funded in Europe. However, a flexible tool seems more and more like a research tool. It’s not clear whether that is what the industry needs.
    - Take an existing tool (perhaps from display manufacturing) and modify for lighting.
- It was also suggested that proposed equipment designs be evaluated based on the cost of ownership (which should be clearly defined and standardized for proposals), and that several other existing metrics for the M.O1 task be eliminated. However, a minimum product size of 6”x6” should be specified in the description.
- Several participants indicated that the task description should specify that project proposals need to show scalability to 2017 target values. For the throughput metric, an intermediate target for 2014 was set at 10,000 m^2/year.

M.O2 Manufacturing Processes and Yield Improvement		
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.		
Metric		**2015 Target**
Yield of good product		80-90%
Early failures in 1st 500 hour burn in		
Panel to panel uniformity	Luminous emittance control	±10% of nominal value
	Color control (SDCM)	4
Process cost		Factor of 2 reduction over current practice

Discussion Points

- It was suggested that this task should include unit operations, or discrete manufacturing steps which aim to improve and reduce costs for a single process. However, proposals should embody an integration plan with an analysis of how the process will fit into a viable manufacturing flow.
- For each OLED architecture and stack the device tolerances needs to be defined so that the manufacturing process tolerances can be established.
- There was heavy emphasis on targeting new processes to improve yield, maintain performance and decrease costs. The methods should incorporate direct feedback process control systems.

M.O3 OLED 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		**2015 Target**
Substrate	Total cost – dressed substrate	$\$52/m^2$
Encapsulation	Permeability of H_2O & O_2	10^{-6} g/m^2/day for H_2O 10^{-4} cm^3/m^2 day atm for O_2
	Cost	$\$10/m^2$

Discussion Points

- The organic stack materials were removed from this task. As the display industry will likely drive the cost of these organic materials down, DOE funding should not be prioritized here.
- This task should not be focused on developing new materials, but should focus on creating low cost processes for developing and manufacturing existing material substrates.
- Participants also stressed the importance that the task should address both integrated substrate and encapsulation materials. There is a lot of opportunity, in particular, to reduce cost of the substrate.
- Several participant soapbox presentations emphasized the need to focus on sustainable, minable and abundant materials. Since indium (in ITO) has limited availability which is heavily controlled by China, more erratic and higher costs may result.
- There was discussion that the M.O3 task should emphasize the importance of meeting the MYPP OLED performance specifications and that it should include a throughput or speed metric.

Overall projections/contributions to cost reduction

Table 7: Manufacturing Roadmap for OLED Lighting Panels (Sheet Processing)

Stage	Units	Year	
		2013	2015
Light output	lm/m^2	6000	10,000
Substrate area	m^2	0.2	0.7
Cycle Time	Sec	120	60
Yield	%	0.8	0.9
Annual Uptime	Hours	3000	6000
Annual Production per line	m^2	10,000	175,000

Discussion Points

- It was estimated that for 2011 the total annual production will be approximately 1,000 m^2, for 2013 this will increase to 10,000 m^2 and by 2015 it will reach 500,000 m^2.

Table 9. Projected Materials Costs of OLED Lighting Panels (sheet processed)

Stage	Units	Year		
		2011	2013	2015
Organic Materials (Material Utilization)	$\$/m^2$	50 (30%)	20 (50%)	10 (70%)
Substrate	$\$/m^2$	50	7	7
Electrodes	$\$/m^2$	30	30	15
Light extraction	$\$/m^2$	20	15	30
Encapsulation	$\$/m^2$	100	15	10
Other materials	$\$/m^2$	20	15	10
Cost	$\$/m^2$	340	122	86
	$/klm	110	20	9

Discussion Points

- The participants indicated that the organic materials metric in Table 9 should also consider utilization. This was determined to be 30% for 2010, 50% for 2013 and 70% for 2015.
- For the substrates cost we are currently in a period of high inflation, therefore the base costs of glass are going up and the 2011 cost is approximately $\$50/m^2$ for display glass. This is expected to decrease once OLEDs move to utilizing soda lime glass which has a cost of ~$\$6/m^2$ (rising to ~$\$7/m^2$ due to inflation).
- The current cost for the electrodes was determined to be about $30/ m^2 based on ITO; however, this is expected to decrease by 2015 to $15/ m^2 due to the switch to using alternative transparent conductors such as zinc oxides or silver nanowires.

- The light extraction costs for 2011 (assuming external film increasing extraction by 1.5x) were estimated to potentially increase by 2015 as performance improvements are made for external and internal extraction layers to meet the MYPP performance objectives (2.2-2.3x extraction).
- Encapsulation costs for 2011 were suggested to be approximately \$100/ m^2 (based on etched pocket processes). However, this is expected to decrease to \$15/m^2 with use of stamped metal can and dessicant structures. This could potentially decrease further with use of direct encapsulation equipment and materials.
- Cost per kilolumen is based on projected luminous emittance. In 2011, luminous emittance of panels is ~ 3000 lm/m^2. This value is projected to increase to 6000 lm/m^2 for 2013 and 10,000 lm/m^2 for 2015.

Presentations

1. **OLED Lighting – If We Aren't Nimble The Future is Dim**
   David Gotthold, Veeco Instruments

- Currently the DOE Roadmap objectives for OLED lighting are not aggressive enough. LEDs are now capable of providing similar performance, lifetime cost and usability compared to competing technologies. In order, to get OLED lighting into the market we need to develop an incremental market penetration path and determine which niche markets are best suited for OLEDs.
  - He indicated that being equivalent to LED is not enough to overcome added risks within the OLED market; therefore, manufactures need to identify and focus on OLED specific target markets for rapid entry.
- David also emphasized that equipment does not need to be a bottleneck for OLED production. However, uncertainty in market timing and scope presents a significant challenge and borrowing off display tools is likely to present cost challenges.
- In order for OLEDs to be competitive a 30 fold cost reduction is necessary.
- Toolsets should be optimized for both initial cost and cost of ownership, however, without government investment, high volume lighting specific toolset will be difficult to justify. Otherwise the U.S. will lose to foreign developers.

2. **OVPD – Key Enabling Technology for Cost-Efficient OLED Manufacturing**
   Rainer Beccard, Aixtron

- OLEDs are consistently become more complex and the future OLEDs may easily consist of upwards of 100 layers. Therefore, we need to work towards enabling complexity.
- Rainer indicates that the use of composition cross-fading (grading layers) improves efficiency and that further OLED developments require gas phase deposition processes in analogy to inorganic LED which can improve both dosing and mixing precision.
- Therefore, the OLED industry needs to consider utilizing OVPD technology. The benefits include, high deposition efficiency, high deposition rate, the ability to deposit multiple layers in one chamber. All of these factors will results in lower TACT and TCO, and hence, cost.

3. **DOE Roundtable Presentation**
   Miguel Friedrich, nTact

- The DOE needs to prioritize innovative equipment for solution processed OLEDs.
- One type of solution processing is slot die base technology (extrusion coating) which is adaptable to sheet-to-sheet and roll-to-roll processes. This method offers low equipment cost of ownership, high material utilization, and low material waste.
- nTact is working to develop pattern deposition methods which eliminate the need for using photolithography, laser ablation or masking processes in certain applications and further improves material utilization. These pattern deposition methods include both selective coating and macro patterning.
  - For selective coating, nTact has developed a technique for depositing multiple, well defined coated areas on a single substrate.

    - nTact has then developed the macro patterning method which provides low-resolution patterning to the coated areas. This method can be used to achieve complex patterns as well as rectilinear shapes.
- Questions/Comments:
    - When do you use selective coating versus macro patterning?
        - Selective coating is used when you are looking at defined areas within one large substrate. When you are looking to coat just one defined area with no need for removal. Macro patterning is for more complex designs.
    - Is there a limit to the web speed?
        - We do not know this limit yet.

4. Realistic Pricing for OLED Panels
Mike Lu, Acuity Brands Lighting

- The highest priority for the OLED industry is getting products to market in the near term.
- In order to achieve this we need to focus on high throughput, high utilization source development, low cost encapsulation and developing substrates with integrated light extraction layer.
- Currently the OLED product roadmap for Acuity is to develop a luminaire with 60-80 lm/W efficacy and lifetime of 15,000-25,000 hours by 2012-2013.
- The exorbitantly priced OLED luminaires with inversely corresponding performance specifications do not present the technology as ready for main stream lighting. The OLED industry cannot focus on niche market products that are unlikely to generate the necessary volume to achieve the economics of scale that will bring down panel prices.
- In order to get the price point down for OLEDs we need to focus on attaining shorter TACT to reduce depreciation, low cost substrates with integrated light extraction, and low cost and robust encapsulation.

5. DOE OLED Roundtable
Dave Newman, Moser Baer Technologies

- The OLED lighting industry has very limited experience in actually running a high yield manufacturing line. This results in a limited understanding of the production yields and unit manufacturing costs.
- Therefore, until the yield can be confidently predicted, and raised to a sufficient level, investments in high volume manufacturing facilities for OLED lighting will remain a high risk proposition.
- When considering the substrate, it is not clear what process controls are necessary and what the required substrate tolerances are to predict yields.
- It is also necessary to consider how the OLED industry can prevent binning and what the sensitivities to variation are (i.e. will there be lifetime and efficiency variations, or color shifts).
- In addition, encapsulation losses must be minimized since significant amounts of product can be lost because of this.

6. **SSL Manufacturing**
   Michael Boroson, OLEDWorks LLC

- In the OLED display industry, early entrants could not reduce cost fast enough, could not sell early products with enough volume and profit, and ultimately could not make the products that consumers wanted. This resulted in the entire OLED display industry moving to Asian entrants who had other display products that they could sell during the transition period.
- We need to recognize that our competitors are LEDs not the fluorescents, particularly the 2 ft' by 2'ft troffer. And to compete with LED in the next 3-4 years OLED lighting panels must cost \$60-120/m^2 to manufacture, so they can then be sold to luminaire manufacturers for \$120-200/m^2.
- Therefore, the highest priority is achieving low cost and high throughput equipment for every step of the manufacturing process (cleaning, light extraction coating, TCO deposition and patterning, OLED vacuum deposition, and encapsulation).
  - Of these the most important is low cost and high throughput OLED vacuum deposition equipment
- If we do not act quickly and effectively display and LED companies will take over OLEDs in 10-20 years if they see a benefit to it. We will also lose the ability to have manufacturing in the US.
- Questions/Comments:
  - China is controlling indium production; therefore we cannot focus on ITO processing which would mean that OLED processing is dependent on indium.

7. **DOE OLED Roundtable**
   Dennis O'Shaughnessy, PPG Industries

- Dennis indicated that the highest priority for the OLED industry is materials. There needs to be support for the scaling up of low cost and high volume manufacturing processes of these materials. The current process line costs for OLED materials are also a barrier to independent development for low demand products.
- In addition, improving integrated manufacturing is of high priority and should focus on the elimination of WIP and non-value added steps, reduced cycle time, and increased area and uniformity. Also specific goal need to be set for gross throughput
- When looking at the OLED deposition and patterning equipment task, we need to give preference to the adaptation of existing tools in order to reduce required capital expenditure for new tools that carry their own development cost.
  - We also need to focus on tools that eliminate defects as opposed to measuring them.
- Lastly for the back-end panel fabrication task we need to focus on avoiding investment in repair.

8. **Critical issues to ensure successful OLED manufacturing**
   Mike Hack, Universal Display Corporation

- Mike indicated that the top priorities for the OLED industry are lowering cost, improving technology and manufacturing equipment, as well as government support.
- For low cost he highlighted deposition equipment and substrate systems. Lower cost can also be achieved through manufacturing processes with lower TACT, higher yields and moving to WOLED devices with simplified device design (approx. 6-7 organic layers)
- In terms of improving the OLED technology, he suggested that there is a need for better OLED performance and lifetime at higher luminances. There is also a need for integrated thin film

encapsulation with low TACT, improved intensity shaping for OLED panels and fault tolerant panel design.

- For manufacturing equipment and infrastructure, Mike indicated the importance of developing fabrication equipment designed for high deposition rate without keeping source materials continuously hot and deposition equipment that avoids bringing chamber to atmosphere to re-load source cells.
- It is also important that the industry work on developing demonstrations and prototypes to show benefits of OLED lighting.
- Lastly, he indicated that it is very important for DOE to continue (or increase) support for U.S. based OLED manufacturing

9. GE R&D Line Configuration
Anil Duggal, GE

- If the OLED industry can get to roll-to-roll manufacturing we have a chance to beat the LED approach.
- We need to focus on getting into general lighting, and enabling roll-to-roll which is essential for penetrating into these types of applications.
- Therefore, Anil suggested a manufacturing process which utilizes wet cost organic layers (processed under atmospheric conditions), a high speed air to vacuum module and then dry coat electrode layer to improve performance.
- Anil indicated that balancing low cost with performance is highly important and that there is significant need for high speed drying, cathode deposition and patterning, and low cost input materials and TCO films

10. 2011 R&D Manufacturing Roundtable - OLED
Gary S. Silverman, Arkema

- Currently the equipment suppliers have too high of a risk to provide for the OLED lighting industry. Therefore, it is essential that we focus on integrating OLED device manufacturing into the full process.
- Gary identified opportunities for processing substrates on a larger scale. In terms of TACT he indicated that with a connected substrate stack process there is potential for 70-85% up-time which is similar to the display industry. He also indicated that it is very important to partner for substrate projects in order to get around IP issues.
- Also emphasized was the need to focus on sustainable materials such as doped ZnO which is minable and abundant compared to ITO (indium) where only 60 MT of indium were available in 2009 compared to the 12.5 million MT for zinc. The continued use of ITO will lead to erratic and high costs.
- Questions/Comments:
    - How long will ITO be sustainable within the industry?
        - This will depend on the restriction imposed by China. As long as they have excess they will export indium.

11. 2011 Manufacturing Roadmap OLED Roundtable
Florian Pschenitzka, Cambrios Technologies Corporation

- For the near term it is highly important that the costs for OLED be reduced. The current target is to reach \$200/m^2, however we are at around \$1000/m^2.
- OLEDs are still lagging behind LED performance in terms of efficiency and lifetime; however they are good enough for early practical applications.
- We need to begin to think about how OLEDs will fit into the general illumination market, since they are not drop-in replacements for incandescent light sources.
- In order to reduce costs he suggests improving brightness through outcoupling with a scattering layer at the glass/anode interface and using larger substrates with direct patterning TC which has a lower cost of ownership compared to sputtering. He also indicated that we need to simplify processing and look to alternative TCs that utilize more abundant materials than ITO and have better material utilization.

12. Roll-to-roll manufacturing of rigid or flexible OLEDs on aluminum substrates
Kirit Shah, Alcoa

- Kirit indicated there is high value in utilizing aluminum substrates for top emitting OLED panels. They offer the potential to reduce cost and improve performance across a wide range of OLED devices and have the potential to meet OLED fabrication and performance requirements while achieving the DOE target of \$6/m^2. Aluminum substrates also provide manufacturing flexibility to encapsulate with glass or plastic depending upon device requirements.
- The material advantages of aluminum include: Low cost, high barrier properties, good thermal management, facilitates panel/luminaire integration, good strength, light weight and recyclability
- He indicated that there are several process advantages for using aluminum as a substrate material as well. These include: potential for high volume manufacturing, roll-to-roll processing, greater manufacturing flexibility, potential to integrate VTE and solution processing and easier handling and transport.

13. Materials and Process Development in OLED Panel Manufacturing
Mathew Mathai, Plextronics

- Matthew suggested that OLED materials manufacturing and process development be the priority funding areas for 2011.
- For materials manufacturing he indicates that achieving materials purity is a must, however we need to establish specifications around incoming materials quality. He also stressed the importance that the purity level established for materials needs to fit the purpose, since not all materials require ultra high purity levels.
- For the suggested new priority task OLED manufacturing process development, Matthew indicated that opportunities exists to lower panels costs via demonstration of improvement in specific unit operations (e.g. substrate preparation, organic layer deposition, electrode deposition, encapsulation). Therefore, we need to focus on demonstrating better materials utilization, lowering cycle time, demonstrating improved yield and creating funding opportunities to lower costs through a partnership with a US based Pilot program.

14. DuPont Input to DOE Manufacturing Plan
Seva Rostovtsev, DuPont Displays

- In order for the OLED industry to succeed we need to realize that materials and processes for OLED lighting will be based on the display industry
- For the deposition and patterning equipment priority task we need to focus on developing nanometer thick OLED layers with <5% uniformity since this is a tremendous coating challenge compared to most other electronic products. The industry also needs to avoid thin layers combined with high fields since this makes OLEDs susceptible to shorting.
- Within the OLED materials manufacturing task, funding is needed to determine alternatives to indium, iridium, and platinum which are expensive and will get more expensive when used for mass produced OLED lighting. Furthermore, research is needed to improve upon existing encapsulation methods which are too expensive and/or have insufficient barrier properties.
- Lastly, he provided several suggestions for the thermal management priority task. These include: The need to quantify thermal sensitivity of the stack, the development of direct thermal contact to OLED stack at the cathode for improved heat sinking, and the need to include thermal management in segmentation design.

15. Overview of Plastic Substrates for OLED Lighting
Robert Rustin, DuPont Teijin Films

- Robert indicated that there are several major challenges for engineered substrates in OLED applications. Some of these include: low coefficient of thermal expansion, low shrinkage, upper temperature for processing, surface smoothness, solvent resistance, moisture resistance, clarity, rigidity, conductive layers and commercial availability.
- Currently OLED manufacturers must leverage products for other markets to meet small scale demands. Also, the size of defects and density must become tighter for OLEDs and since current measurement systems do not exist for volume quality control so we must rely on ineffective spot measurements.
- Lastly the US must consider global supply chains and producers must design for “best in class” global standards.

DOE OLED Roundtable Participants

Rainer Beccard	Aixtron
Michael Boroson	OLEDWorks LLC
Anil Duggal	GE
Miguel Friedrich	nTact
David Gotthold	Veeco Instruments
Mike Hack	Universal Display Corporation
Mike Lu	Acuity Brands Lighting
Mathew Mathai	Plextronics
Dave Newman	Moser Baer Technologies
Dennis O’Shaughnessy	PPG Industries
Florian Pschenitzka	Cambrios Technologies Corporation
Seva Rostovtsev	DuPont Displays
Robert Rustin	DuPont Teijin Films
Kirit Shah	Alcoa
Gary S. Silverman	Arkema