Solid State Lighting OLED Manufacturing Roundtable

INTRODUCTION

On March 17, 2010, 14 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 some of 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 put forward these suggestions at the SSL Manufacturing Workshop. This work will guide the DOE in selecting funded projects in OLED manufacturing during the coming year.

TASKS

The table below summarizes the tasks discussed with their associated metrics. Cost is a metric for all tasks and all work must demonstrate compatibility of the proposed approach with the other portions of the manufacturing process and with DOE OLED cost and performance targets. A more detailed description of each task with relevant discussion points from the roundtable is presented in the next section.

	Task	Metric
M.O1.	**OLED deposition and patterning**	Throughput Uniformity Materials Utilization Registration and Resolution
M.O2.	**In-line monitoring tools**	Speed Yield Improvement Waste Reduction
M.O3.	**OLED materials manufacturing**	Purity Performance as Deposited Compatibility
M.O4.	**OLED panel fabrication**	Panel Reliability Reproducible Performance
M.O5.	**Integrated OLED manufacturing**	Throughput Panel Reliability and Reproducibility Panel Performance Design Flexibility

M.O1. OLED deposition and patterning

Support for the development of manufacturing tools (compatible with the rest of the manufacturing process) enabling high speed, low cost, uniform deposition, and/or patterning of state of the art OLED structures and layers. Tools can fall into three categories of equipment – substrate, OLED manufacturing, and encapsulation. This includes the development of new tool platforms or the adapting of existing tool platforms to better address the requirements of OLED lighting products. For example, this could include the modification of glass coating tools to create large area substrates with integrated electrode, charge injection, and/or light extraction layers; or OLED deposition tools for displays can be retooled for the requirements of higher speed, white OLED deposition for lighting. Forecasts must be provided of the total cost of ownership and operation for the tool, including labor and infrastructure requirements, such as material handling and environmental control.

DISCUSSION POINTS

- Leverage as much as possible from OLED display manufacturing to minimize OLED SSL development costs and maximize speed to market.
    - Don’t reinvent anything from scratch if it can be avoided.
    - Make sure technology and cost improvements can be applied to both lighting and displays.
- Determine which equipment minimizes environmental demands on-line.
    - This will help the market adaption since one main value of OLEDs is the “green” proposition.
    - If the equipment is not designed or used in an environmentally-friendly manner, then the OLED public perception could easily be tainted making market adoption more difficult.
- Sheet coating and printing to demonstrate substrate tool using pilot trial.
    - Aim for target sheet resistivity, transparency, homogeneity, roughness, and adhesion. Substrate tools are one of three main tools for investment.
- Develop uniform, clean, and fast-drying solvent.
    - Ensure even deposition.. This is difficult to do in inert environments.
- Verify incoming materials quality and improve quality control.
- Adapt high-rate deposition tool able to manufacture multiple layers effectively, perhaps accommodating tandem structures.

M.O2. In-line monitoring tools

Support for the development of in-line monitoring tools for rapid feedback of the manufacturing process. Tools could include optical monitoring tools for defect detection and layer deposition uniformity or tools to rapidly measure barrier coating performance. Tools must demonstrate compatibility with existing manufacturing approaches and demonstrate cost reduction and/or improved quality and yield of the OLED products.

DISCUSSION POINTS

- Process control methodologies must be developed. Monitoring and controlling processes will improve overall manufacturing efficiency. However, this has the potential to add cost to overall system. If controls go down, then the whole system will be offline until control system is repaired.
- Continuous testing during processing is important
    - Instead of testing batches, it will provide instant feedback to the manufacturers of the quality of the products. This will allow manufacturers to immediately correct any defects in the line.
- One area that this could be useful is in measuring the doping ratio as product is made
    - Currently only indirect measurements (crystal monitors) are used
    - There is not enough data on batch-to-batch variability, or within batch variability of doping.

- Another area of interest could be online monitoring of plastic substrate manufacturing. Testing after manufacturing can take 24-48 hours. Thus, a company could be making poor quality materials and not realize it for days.

M.O3. OLED materials manufacturing

Support for the development of advanced manufacturing of organic and inorganic OLED materials to increase material production volume while reducing costs and improving consistency and purity. Tools or processes should demonstrate compatibility with state of the art OLED lighting device structures and with existing OLED manufacturing approaches.

DISCUSSION POINTS

- Scale-up from laboratory to mass-production volumes.
- Should include handling, storage and waste disposal methods.
- Must anticipate and address interface issues.
- Could involve substructures e.g. plastic substrate with barrier layer.
- Develop processes that facilitate manufacturing for high-quality materials. Higher quality materials typically yield higher quality products increasing overall lifetime and efficiency.

M.O4. OLED panel fabrication

Support the development of tools and processes for the manufacturing of OLED panels from OLED sheet material. This includes the singulation, packaging, and necessary testing 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.

DISCUSSION POINTS

- Optimize packaging and reduce packaging cost
- Should ensure good thermal management

M.O5. Integrated OLED manufacturing

Support for the integration of OLED manufacturing processes and the production of prototype panels. This work should explore the compatibility of materials, processes and tools and provide the capability to optimize the use of each component. Predictions of manufacturing parameters, such as throughput, yield and cost should be tested and reported. The production of panels should serve both to provide samples for luminaire manufacturers and to provide data on the performance, reliability and consistency of the finished product. Flexibility to incorporate alternate selections of materials or process is essential.

DISCUSSION POINTS

- Evaluate and validate various manufacturing approaches
- Collaboration is essential to determine compatibility of approaches and components in the final OLED panel.
- Will determine the best set of tools and processes in manufacturing
- It is important to demonstrate reproducibility
- Reliable integrated manufacturing will provide market test samples and build consumer confidence
- This is the overall charter. Once the market test samples are evaluated by the end customer, it will provide valuable feedback to the manufacturers and designers what should be done for further market adoption and mass manufacturing.

RECOMMENDATIONS FOR CORE/PRODUCT DEVELOPMENT

- Develop components with integrated functionality such as substrates with transparent conductor, light extraction, current spreading, and/or charge injection functionality.
- Develop OLEDs with simplified/manufacturable device structures with state of the art performance and possible integrated light extraction technology.
- Develop manufacturable barrier coating technologies.
- Develop substrates (e.g., plastic, foil, or glass) that are low cost, defect tolerant, and compatible with manufacturing processes.
- Develop manufacturable light extraction approaches.
- Develop OLED structures that allow for intensity shaping of the emitted light while maintaining uniform color.
- Using high glass transition temperature materials is important – for operational purposes and in the manufacturing process.
- The product design must also be optimized for electronics, pairing the panel and drive together, and creating a power supply design.

GENERAL RECOMMENDATIONS FOR SSL PROGRAM

- Make specifications
  - Specifications are broken down into product, processes, tool, and packaging specifications
  - Define panel (luminaire) specification
  - Translate product specification to process specification to guide manufacturing investment
- Define and partition processes
  - This is the first step in producing a pilot line. It is critical to have collaborative process definition. This must begin with customer input.
  - Clearly defined processes will help determine which to test and invest in.
- Define and partition tools
  - Use the defined manufacturing processes to determine which potential tools will be needed. Tools are needed for the substrate, OLED, and encapsulation.
  - Clearly defined tools will help determine which to test and invest in.
- Define and partition interfaces
  - Clearly defined interfaces will help deal with IP considerations for interfaces between layers, systems, and different companies
- Develop repair strategy and materials recycling operation
  - Minimize waste and reduce materials cost
  - Must find way to deal with hazardous and certain volatile organic compounds
- Investigate international standards because some companies like Osram and Phillips have been selling OLEDs overseas.
- Fund materials and tools development as well as OLED manufacturing
- There needs to be an analysis of the energy payback time. i.e. how much energy does it take to manufacture a panel and when does that payback?

PRESENTATIONS

Below summarize the soapbox presentations given by the attendees of the SSL OLED manufacturing roundtable.

1. Intensity Shaping and Color Quality Requirements of OLEDs
Peter Ngai, Acuity Brands Lighting

- Intensity shaping determines the appropriate illumination coverage and controls glare. Depending on application, a narrow or wide light distribution is required. Thus, OLED luminaires need flexibility in intensity shaping.
- Two types of glare to consider: high angle (or far light source) glare and overhead glare.
    - At higher angles, you approach your viewing angle and thus want less intensity.
    - At greater than 10,000 cd/m^2, high angle glare becomes a problem.
- The CIE (International Commission on Illumination) coined a term called UGR (Unified Glare Rating) that is the general formula for assessing glare. The IES is considering adopting UGR. RP1 is what is currently used in the US.
- OLED Color Requirements
    - High CRI (80+) with R9
    - CCT 2800K-4000K
    - Color consistency at different viewing angles, among different OLED panels, through lifetime, and at different input powers (for dimming).

2. Meeting \$100/m^2 Manufacturing Technology

Gopalan Rajeswaran, Moser Baer Technologies

- Moser Baer/UDC estimates that by 2012/13, unit manufacturing cost will \$250/m^2 assuming annual product shipments of 5,500,000. Results in < \$25/klm at 3000 cd/m^2. (Does not include the driver cost). This exceeds the existing target in the roadmap of \$300/m^2.
- Reaching the 2014 target of <\$100/m^2 total direct costs requires innovative integrated manufacturing technology concepts
    - Costs across the board (not just of one component) must come down
    - To meet the target, there needs to be demand for the product and an avenue for customers to purchase the products.
- Cost effective solutions in substrate, OLED and encapsulation technologies must be encouraged with results to be demonstrated in an integrated manner (not in isolation).
- The US DOE SSL program must solicit manufacturing technology RFPs that are collaborative in nature among US supply chain aspirants and capitalizes on DOE funded R&D/Product programs & the forthcoming US OLED manufacturing infrastructure
- The materials industry is an extremely nebulous and fragmented industry. However, the display industry has been taking off. Could potentially take the display industry and use that to help standardize the materials industry.
- Encourage the creation of an OLED materials industry in the US capable of delivering HIL, HTL, ETL, EIL, BL layer materials (industry is fragmented, mainly in Asia)
    - It is more lucrative to supply hosts, rather than just dopants.
    - Needs to be a materials supplier who can license out the materials, or buy directly from the suppliers. There will not be a one stop shop but it won’t be necessary for the companies to go through integration from ground zero.

3. Critical Issues to Ensure Successful OLED Manufacturing

Michael Hack, Universal Display Corporation

- Successful manufacturing will involve: cost reduction, correct technology, equipment infrastructure, and government support
- Cost Reduction
    - Faster TACT time for manufacturing processes
    - Lower cost for substrate systems
    - Lower capital cost for deposition equipment

    - High material utilization deposition equipment
- Technology
    - Need higher luminances while maintaining lifetime
    - Integrated outcoupling enhancement into device architecture for thin form factor
    - Integrated thin film encapsulation with low TACT time
    - Panel intensity shaping
    - Reproducibility studies
- Equipment/Infrastructure
    - Deposition equipment designed for high deposition rate without keeping source materials continuously hot
    - Deposition equipment that avoids bringing chamber to atmosphere to re-load source cells
    - Demonstrations and prototypes to show benefits of OLED lighting
- Government Support
    - Metal substrates for rugged flexible form factor and cost reduction
    - Integration studies for new manufacturing strategies and lower cost equipment
    - Development of OLED luminaires for customer acceptance
    - Standards to promote product acceptance
    - Policy to accelerate adoption of “green” energy saving SSL

4. Roll-to-Roll OLEDs

Anil R. Duggal, GE Lighting

- Since LEDs are competing in the diffuse light source market, OLEDs should focus on the low cost potential at an acceptable return on investment. This is why GE chose roll-to-roll.
- First need to figure out the highest performance devices, test the manufacturing processes, before investing in any single method→pilot scale manufacturing research is critical!
- We aren’t going to see Gen 7 or Gen 8 plants because we need to lock down all the process steps before making large capital investments.
- For marketing, must focus on the unique traits of OLEDS (thin, flexible, transparent)
- Comments on the roadmap:
    - Sheet and web processing should be about the same cost. But the capital investment cost is much lower for roll-to-roll.
    - OLED organic materials will be made in large quantities eventually and is not a trivial cost. Continue the discussion with how to decrease the cost.
    - It should be noted that the roadmap projections do not represent full production, just a pilot line.

5. DOE Manufacturing Funding Opportunities

Daniel LeCloux, Dupont

- The challenges for OLED SSL manufacturing include: lowering cost, decreasing power consumption and increasing lifetime while maintaining low cost components and processes, demonstrating reliability with mass production, leveraging existing technologies from OLED display technologies.
- Develop simplified architectures with 2-3 layers and micron thick layers in the OLED stack (to improve yield and decrease shorting)
- Use sustainable (less expensive or rare) materials. In particular, find an alternative to ITO and high IQE emitters that don’t use precious metals.

- Lower the cost of and improve barrier properties of encapsulation by eliminating cavity glass or getters, integrating it into a continuous process post cathode deposition, reducing TACT time to less than 1 minute, and using cheaper materials.
- Thermal management needs to improve because as operating temperature increases, luminance decreases. One way to do this would be to apply a direct thermal contact to OLED stack at cathode for improved heat sinking (used in combination with thin film encapsulation on cathode).
- Improve efficiency by enhancing outcoupling while maintaining low cost and process compatibility.
- Improve plastic substrates to enable simple fabrication. Improvements include reducing cost, integrating the barrier, improve solvent and high temperature resistance, and improve outcoupling.

6. Materials and Ink Manufacturing Process Development

Mathew Mathai, Plextronics

- Scaling up materials and inks are important because they are at the front end of the manufacturing process. Panel manufacturers need reliable suppliers
- Provided the following input to the manufacturing roadmap (in italics are new/modified topics that facilitate materials and inks manufacturing and process development):

Topic	**Development Area**	**Proposed Approach**
Cost Reduction	Materials utilization Manufacturing yield	*Joint activity – tool and material provide, development of COO data* Defect tolerant manufacturing
Substrates and Transparent Anode	Planarization Surface roughness Elimination of scarce materials	*Planarization strategies to future proof incorporation of lower cost substrates and electrodes*
Deposition of Organics	Deposition speed Thickness Uniformity Materials utilization Uptime *Stable interface engineering*	*Tool & material/ink trial runs* *Process development* Exploit wet processes with high utilization Trial runs, tool system design *Process & ink/material development*
Patterning Techniques	Edge definition Removal of organics Mask-less deposition	Start with available tools with potential for good film quality, develop methods for patterning
Inspection and Quality Control	In-line tool integration	*Joint project to utilize available tool and design on targeting organic film coating*
Material and Ink Scale-up	*Manufacturing cost* *Establish purity requirements* *Design for manufacture*	*Scaled-up unit operation design* *Robust quality control* *Scaled material and ink production*

7. OLED Substrates

Gary Silverman, Arkema

- A potential barrier for OLEDs is supply side scaling. The OLED market is currently nebulous and though DOE SSL manufacturing funding reduces risk, there are still significant risks for suppliers. The must invest the development costs and time.
- Substrate issue #1: Processing on larger scale

    - Reduce TACT time
    - Maintain environmental control
    - Interface between layers, systems and other companies - Must deal with significant IP especially when dealing with the interface between the layers, systems, and different companies
- Substrate issue #2: work-function mismatch. Using a top coat (<10 nm thick metal oxide)/TCO combination allows for:
    - Allow for scalable (tunable work function) processing versus organic HIL/HTL
    - Decrease or potentially eliminate current organic HIL/HTL
    - Improve TCO interface/planarization
    - Enable easier charge injection
    - Enable wider band gap emitters, especially phosphorescent triplet emission
    - Potentially longer device lifetime by driving the device at lower voltage

8. OLED Manufacturing and DOE Funding Priorities

Steve Van Slyke, TechnoCorp Energy

- Achieved 2009 best performance OLED panel–2.5 x 2.5 cm:
    - Internal Extraction structure: efficacy
    - Tandem architecture: can reduce current density and increase lifetime. However this also leads to the increased cost of more complex structure and more layers.
    - Serial connected structure: cost play because diodes are formed laterally leading to higher voltage and lower current device.
    - Short reduction layer: yield
- Funding priorities
    - Pilot line for tandem device with a short reduction layer with monolithic with performance of >70 lm/W and > 35k hours lifetime
    - Equipment and process development with high material utilization sources that is capable of tandem formats.
        - Deposition tool
        - Monolithic patterning on large sizes
    - High volume manufacturing will help create an infrastructure: Need high throughput of 1M m^2/year to invest $100M capital

9. Float Glass as a Substrate

Harry Buhay, PPG

- PPG is the largest manufacturer of certain glass in the US. Currently much of the glass is going toward PV technologies.
- Float glass is a viable substrate and is atomically smooth, cost-effective, and transparent.
- an integrated product by combining anode and light extraction, and has
- PPG teamed with UDC to manufacture an integrated substrate product- soda lime glass combining the anode and light extraction. A Na barrier coating is available if needed.
- Barriers are
    - New float glass composition requires high volumes to justify investment
    - Lacking experience in OLED manufacturing
    - Risk/uncertainty of return on capital investment
    - Having knowledge of safety requirement for overhead lighting (e.g. weight)
    - Bent glass curved shapes to broaden market for rigid substrate; but requires bent coating capabilities

- Outcoupling is important because there is a tremendous variety in the results. It is a good area for investment.

DOE OLED ROUNDTABLE PARTICIPANTS

Thomas Clausen	3M Display and Graphics Business
Peter Ngai	Acuity Brands Lighting Inc.
Gary Silverman	Arkema Inc.
Karl Pichler	Cambrios Technology Corporation
Daniel LeCloux	DuPont Displays
Robert A. Rustin	DuPont Teijin Films
Amal Ghosh	eMagin
Miguel Friedrich	FAS Holdings Group LLC
Anil R. Duggal	GE Global Research
Gopalan Rajeswaran	Moser Baer India LTD
Mathew Mathai	Plextronics
Harry Buhay	PPG Industries Inc.
Steve Van Slyke	TechnoCorp Energy LLC
Mike Hack	Universal Display Corporation

Appendix: Cross-References Between Manufacturing Tasks and the 2009 Roadmap and 2010 MYPP

If you are interested in participating in the discussion for an individual task listed below in bold, you may wish to read more by referring to the Roadmap and MYPP sections listed below each task. Unless otherwise noted, cross-references are to the 2009 Manufacturing Roadmap.

M.O1. OLED Deposition and Patterning
Section 3.1 (Tables 4–7)
Section 3.3
Section 3.4
Section 3.5
Panel/Luminaire Projections (Tables 4.7–4.8 of 2010 MYPP)

M.O2. In-Line Monitoring Tools
Section 3.4.4
Section 3.5.5
Panel/Luminaire Projections (Tables 4.7–4.8 of 2010 MYPP)

M.O3. OLED Materials Manufacturing
Section 3.1 (Tables 6–7)
Panel/Luminaire Projections (Tables 4.7–4.8 of 2010 MYPP)

M.O4. OLED Panel Fabrication
Section 3.1 (Tables 4–7)
Section 3.2
Panel/Luminaire Projections (Tables 4.7–4.8 of 2010 MYPP)

M.O5. Integrated OLED Manufacturing
Section 3.1 (Tables 4–7)
Section 3.2
Panel/Luminaire Projections (Tables 4.7–4.8 of 2010 MYPP)