Solid State Lighting OLED Manufacturing Roundtable Summary

Introduction

On April 17, 2012 sixteen OLED experts gathered in Washington, D.C. 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 priority tasks, a summary of discussion points relevant to those selections (not all necessarily in support), and a short summary of the soapbox presentations.

General Roundtable Attendee Comments

- The main themes of the OLED roundtable presentations were:
  - Cost as it relates to substrate and encapsulation.
  - Cost of OLED stack materials
  - Cost of entry into OLED manufacturing. Cost of tools and upfront investment as well as return on investment considering the predicted market demand.
  - Cost as it relates to yield and process improvements.
- Innovative developments in OLED manufacturing are necessary; therefore it is essential that potential projects propose novel cost reduction solutions for OLED manufacturing.
- There is no unanimous agreement on the best mechanism for cost reduction. Some indicate that cost reductions through immediate shifts towards high volume production are essential; while others argue starting small (lower investments) and building up is a better method.
- Regardless of production scale, yield is always a paramount driver of cost.
- Among attendees there is a lack of agreement on the envisioned form factor of OLED panels. Some feel that flexibility and novel features such as transparency or color tunability are important in order to capture a niche market to stimulate interest in OLEDs, consumer acceptance, and demand. Others feel that cost issues are so important that initial devices should be kept as simple as possible to achieve the lowest price point possible.
- More collaboration amongst the supply chain is essential for timely progress to performance and cost goals.
- The DOE needs to foster collaboration between OLED manufacturers and equipment and material suppliers to ensure compatibility of all systems.
- The lack of standards in the OLED industry is an area of concern.
  - If a standard OLED stack is prescribed, this could help guide tool manufacturers and substrate developers create products that are compatible with state of the art devices and useful to panel manufacturers. Further, such a standardized stack could allow panel manufacturers to compare substrate performance and manufacturing level control between various suppliers.
  - A standard panel could accelerate luminaire development and integration.

    - Standard measurement protocols and/or standards on substrate performance and materials could help guide substrate developers.
- Attendees discussed Task M.O4 Back-end Panel Fabrication but did not identify it as a research priority for OLED manufacturing.
- OLED stack material costs are very high and not likely to be excessively reduced. The main need in OLED stack materials is Core R&D in the development of higher performance materials, rather than Manufacturing-based R&D efforts.
- There is concern as to whether support for the manufacture of OLED deposition equipment (M.O1) and OLED materials (M.O3) is in best alignment with the DOE goals. There is uncertainty as to whether the DOE objective is mainly for the U.S. manufacture of OLEDs or to support worldwide efforts in OLED manufacture that will ultimately lead to domestic energy savings.
- There is concern that the U.S. is too far behind in their panel manufacturing efforts to compete with countries that are either already beginning to produce OLED lighting products and/or are successful display manufacturers. The fact that many countries subsidize these efforts, allowing for lower cost products puts U.S. companies at a further disadvantage.
- U.S. materials manufacturers, substrate manufacturers, and equipment manufacturers can be and are quite successful.
- Well developed display technology could be leveraged to advance OLED lighting, including display equipment, structures (top-emitting vs. bottom-emitting for example) and materials. However, OLED displays have different architectures and performance specs to meet and thus there are display tools, structures and processes which do not necessarily product good quality OLED lighting panels.
- Manufacturing of OLED lighting panels will initially be primarily through vapor deposition processes, then a hybrid approach using some solution processing as well as vapor deposition, and finally, manufacturing may rely on solution-based processing when OLED demand is high and prices are further reduced.

Proposed Priority Tasks

The following tables provide descriptions and metrics for the proposed priority tasks. The task tables shown do not reflect any modifications suggested by roundtable attendees. All comments, including suggested changes to each task description and metrics, are provided below each of the relevant task tables. These comments represent a summarized transcript of the general commentary and require further discussion at the Manufacturing R&D Workshop. The results of these discussions will guide the DOE in soliciting projects in the LED Manufacturing R&D Program during the coming year.

<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="7">Throughput</td><td>Overall throughput</td><td>100,000 m^2 per year</td></tr>
<tr><td>Minimum product size</td><td>6” x 6”</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">Materials utilization</td><td>Dry process on sheets: 70-80%
Wet process on web: 90-95%</td></tr>
<tr><th colspan="2">Attendee Suggested Metrics</th><th></th></tr>
<tr><td colspan="2">Processing cost/unit</td><td>$100/m^2 or $/klm</td></tr>
<tr><td colspan="2">Initial/capital cost</td><td></td></tr>
<tr><td colspan="2">Cost reduction (1x)</td><td></td></tr>
</table>

Roundtable Attendee Comments

Proposed changes to description

- This task should call out the need for the development of machines which can produce high performance OLED stacks. To show real progress toward manufacturability, this task should explain that equipment must be demonstrated on several relevant emissive layer formulations (this is more applicable to VTE or VTE-like solutions).
- There is a need for DOE to foster collaboration between OLED manufacturers and equipment and material suppliers to ensure compatibility of all systems. The task description needs to include a note that collaboration should be expected between the equipment and material industry.
- The description should emphasize the importance of reducing machine costs. The cost advantage of the proposed equipment would be difficult to define with a metric as it depends on the type of equipment and overall contribution to total cost OLED manufacture. Thus, applicants should be

encouraged in the description to provide a detailed cost analysis of the proposed equipment as compared to current state of the art equipment and future needs.

Proposed changes to metrics

- The ‘overall throughput’ metric of 100,000 m^2 per year of good product should be removed.
- The 2015 target for the ‘minimum product size’ metric should be changed to 100 cm^2 (4” x 4”).
- The 2015 targets for ‘area utilization’ and ‘uptime of machine’ should both be changes to >80%.
- The ‘speed (web)’ metric should have a 2015 target of > 2m/min.
- A metric for ‘processing cost per unit’ needs to be added. A 2015 target for this metric could be \$100/m^2. However, a target for this metric could be expressed in terms of dollars per square meter or dollars per kilolumen.
- ‘Initial/capital cost’ and ‘Cost reduction’ metrics could be added.

Other comments

- There is a need for novel low cost manufacturing methods in order to enable profitable market entry for panel makers and luminaire manufacturers. The proposed manufacturing methods cannot ignore depreciation or labor costs and must be scalable and profitable from low early volumes to high future volumes.
- High volume equipment must have high efficiency and very high feed rates to achieve necessary deposition rates and cost targets. The equipment must also be flexible, robust and controllable in order to enable production at a variety of sizes and deposition rates.
- In order to reduce manufacturing costs, high volume production is essential. However, starting manufacturing at a small scale for development of the product would avoid the prohibitive initial investment required for high volume production equipment.
- Reducing the cost of OLED deposition equipment is important. Using a tool with a small footprint and developing more integrated equipment systems (even at the R&D scale) could help with these costs.
- The usefulness of manufacturers initially utilizing repurposed equipment as a stepping stone to investing in upgraded equipment is unclear.
- Moving toward low cost, high throughput automated systems is important as the machines and the necessary industry structure do exist.

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**
Reliability	Yield of good product	80-90%
Process cost		Factor of 2 reduction over current practice
Early failures in 1st 500 hour burn in		
Panel to panel reproducibility	Luminous emittance control	±10% of nominal value
	Color control (SDCM)	4
Attendee Suggested Metrics		
Total product yield		

Roundtable Attendee Comments

Proposed changes to metrics

- The metric for ‘yield of good product’ should have a 2015 metric of >80%.
- The 2015 target for ‘color control (SDCM)’ should be changed from 4 to 2.
- A ‘luminous emittance control’ of ±10% of nominal value is a reasonable 2015 target.
- For the ‘process cost’ metric, it is agreed that the 2015 target should be consistent with the MYPP, however, the description needs to emphasize that DOE is looking for “step” and “break-through” changes equating to 10-fold process cost reductions.
- A metric for ‘total product yield’ is proposed. However, this metric would also affect the process cost metric as higher yield equates to lower cost.

Other comments

- Current encapsulation processes are very expensive. Testing and improving encapsulation film is particularly an issue since testing time is very long due to the slow pace of the diffusion process.
- The need for improved test procedures and quality control for encapsulation should be added to this task. This issue is inherent to all the newer plastic films for encapsulation.
- Improvements in this task area are necessary for system-level cost reduction. Until yield can be confidently predicted, and raised to a sufficient level, investments in high volume manufacturing facilities for OLED lighting will remain high risk.
- OLED panel manufacturers need to lead collaborative efforts in this task with tool and material manufacturers to increase the potential for significant yield improvements.

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	$\$52/\text{m}^2$
	Transmission	>85%
	Surface Roughness	Rrms < 2nm Rpv < 20nm
	Sheet Resistance	< 10 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	$\$10/\text{m}^2$

Roundtable Attendee Comments

Proposed changes to description

- The task description needs to include the definition of a dressed/ integrated substrate and whether it includes light extraction, patterning, grid work, etc.

Proposed changes to metrics

- The 2015 target for 'total cost – dressed substrate' should be changed to $\$50/\text{m}^2$.
- When purchased in small research-scale quantities, the base substrate material (polished ITO on borosilicate glass) without any light extraction layers is around $\$200/\text{m}^2$ and the process for the ITO deposition and patterning alone is roughly $\$50/\text{m}^2$. There is a great opportunity for major cost reduction in this area.
- The 2015 target of $\$10/\text{m}^2$ for the 'encapsulation cost' metric is aggressive but realistic. The cost of desiccant material is surprisingly high.

Other comments

- OLED panel cost is dominated by the substrate and encapsulation.
- DOE emphasis on the quality of substrates and electrodes is a priority as it affects yield and hence cost.
- There is a need to enable novel low cost integrated substrates and encapsulation materials. This will require a diversion from OLED display industry methods for materials manufacturing.
- Substrate encapsulation should not be prioritized as it is not going to dramatically affect the overall OLED panel cost. DOE should focus on how to reduce the manufacturing costs from $1000 to$100 either via processes or equipment (i.e. M.O1 and M.O2).

Presentations

1. **OLED "Light-Engine" Modules for Luminaire Integration**
   Nikhil Taskar, WAC Lighting
   - OLED manufacturing needs to focus on developing OLED modules for integration into luminaires. Though none of the tasks accurately describe this need, M.O4 is most relevant.
   - From a system integrator perspective, a hybrid LED-OLED solution might be the best option.
     - Leveraging OLED flat panels for their low glare attributes for direct lighting and using an indirect light solution based on LED light engines.
   - Can an OLED based solution in a luminaire be made as a module? Can a module be designed with the electrical-mechanical connectivity that allows panels to be interchanged based on the color temperature and photometrics that are desired? These questions tie into the compatibility of the device with available power management solutions for inorganic LED solutions.
     - Compatibility with existing drive and electronic controls in SSL will be important to the cost structure.
     - It is not desirable for the majority of the cost to be associated with the electronic/drive parts. The goal is to reduce the overall total cost of ownership.
   - Increasing the color consistency between identical products is also important since it has been shown that the human eye can detect a SDCM of 3.
     - As luminance drops down, sensitivity to color differences between panels will be greater.
       - This is especially true as the luminance levels drop to a few thousand nits as they can be directly viewed.
   - In terms of application specific customization, application efficacy (i.e. the light that reaches the desired application area) matters most in lighting solutions.
   - Regarding cost in dollars per kilolumen for low glare applications, how do we compete with LED edge-lit solutions that are constantly decreasing in cost?

2. **US-based OLED Manufacturing**
   Jerry Liu, GE Global Research
   - In order to create a successful business providing OLED lighting solutions, it has to be profitable. Color quality, efficiency and lifetime are technology driven factors, however in order to create a successful OLED industry the focus needs to shift towards manufacturing for volume.
     - Low capex and low volume with a negative return on investment (ROI) is not marketable. We need to move to high capex and high volume with a positive ROI. There has been good technological progress for OLEDs; therefore we need to begin moving to high volume manufacturing.
   - Task M.O2 should be the top funding priority. This is a key enabler for low capital expenditures and high volume manufacturing. Focusing on task M.O2 also has the potential to give the U.S. an edge above foreign competition.
     - To accomplish this task, broad collaboration is needed. The EU and Asia have established consortiums, however within the U.S. only company-company collaboration exists.
       - If the DOE could help foster a broader collaboration, U.S. OLED manufacturing will benefit as a whole.
     - Also helpful would be to reduce cost by using lower cost, retired equipment suitable for OLED production, such as used display equipment.
   - Task M.O3 also deserves prioritization as it is necessary for system-level cost reduction. Combined tasks M.O2 and M.O3 will have the greatest impact on lowering cost.

3. DOE OLED Roundtable April 17, 2012
David Newman, Moser Baer

- Reducing unit manufacturing costs is an ongoing challenge. Yield and process optimization are two large factors.
  - Until yields can be more accurately predicted and levels increased sufficiently, investments in high volume manufacturing will remain a high risk proposition.
  - OLED device architectures must be optimized to match the process latitude on the specific equipment to be used for manufacturing, with the goal being high yield, and no "binning" of OLED devices for color or other variations.
- Substrates pose an opportunity for major cost reductions. Currently, patterned substrate costs are more than 20-30 times the 2015 DOE Roadmap target of $52/m^2.
- Current encapsulation practices involve using glass or metal foil with an internal desiccant. There are several issues with current substrates, namely internal and external light extraction.
- Many thin film encapsulation R&D activities have been undertaken, but none have been able to achieve the level of process capability needed at an affordable cost.
  - Similar commercially viable processes would enable the development of molded or flexible plastic substrates with moisture barriers.
  - Thus the issue of encapsulation and developing plastic substrates with a barrier layer are big opportunities.
- Another opportunity for cost reduction is improving OLED material utilization. Currently material utilization is between 5% and 15%. These levels need to be improved to over 50%.
- Reduce manufacturing time by increasing equipment throughput rates and improving yield will also help reduce costs.

4. How can the DOE Accelerate Energy Savings in the US by Enabling Low Cost Manufacturing of OLED SSL
Michael Boroson, OLEDWorks LLC

- Reducing cost is the key to achieving the DOE manufacturing targets. A 4-inch panel needs to sell for under $100/unit.
- Currently, panel efficacies are at levels reasonable enough for a first product. What is not adequate is the current cost. We need to increase OLED lighting market share by selling sufficient performance at a reasonable cost. If the cost is low enough, lighting designers and luminaire manufacturers will find applications for which consumers will purchase OLED lighting products.
  - However the manufacturing processes and equipment currently used will not be able to meet cost targets.
- Tasks M.O1 and M.O3 should be made funding priorities.
- In the effort to reduce costs, the highest priority is developing low cost, high throughput and highly automated equipment for every step of the manufacturing process (Task M.O1).
  - Labor and depreciation costs are high but the highest cost is OLED stack deposition.
  - M.O1: We need to develop and enable novel, low cost manufacturing. We need to enable profitable market entry for panel makers and luminaire manufacturers without ignoring depreciation and labor costs. The DOE should help lower the barrier of entry so more U.S. companies can begin making panels.
    - Unlike Asia and Europe, the U.S. cannot simply throw money at the issue. Nor can we mimic the display community's methods. We need a novel approach.
- The second priority should be to lower the costs of the integrated substrates and encapsulation (Task M.O3).

- M.O3: We must enable novel low cost supply of integrated substrates and encapsulation materials.
  - DOE should fund low cost integrated substrates and encapsulation to decrease the risk of installing equipment during the early lower volume market.
- The DOE 2012 estimate for the cost of OLED materials is $40/m^2; however this is closer to $150/m^2. The current cost of the integrated substrates and encapsulation materials is around $300/m^2 and material utilization is at best 20%.

5. **No Presentation Slides**
Jeff Meth, DuPont
- The cost of OLED materials is an important issue and better materials need to be developed. However, all the known low cost synthetic routes have already been explored so further advances will entail harder chemistry.
  - Scaling up OLED material production will pose an additional challenge.
  - The manufacturing target cost of $100/m^2 is very low considering the material costs involved.
- Making a good performing OLED panel requires negligible to no defects. However, this level of precision comes at a high cost.
- From a risk factor point of view, SSL faces a big adoptability challenge. Consumers who purchase OLED lighting products will have to replace what is installed with an OLED luminaire since none are compatible with current lighting systems.
- Another risk is the uncertainty of whether OLEDs, even with rapid improvements, can gain a large enough market share to be viable. Will OLED lighting be able to compete with LED-based lighting and other lighting technologies?

6. **DOE OLED Manufacturing R&D Roundtable**
Dennis O'Shaughnessy, PPG Industries, Inc
- Efficiency, brightness, lifetime and cost are all important drivers for OLED lighting. If OLEDs achieve the DOE targets for these metrics, OLEDs will become a successful market product.
- The question is how to invest in manufacturing equipment and processes if the demand is not high enough to run that equipment at a level that allows one to spread the capital costs over large volumes?
- The main cost drivers are scale and process efficiency. Need to maximize throughput over as large a scale as possible.
  - Variable cost, material yield and line width utilization are also important factors.
- The DOE should fund the development of large scale, high efficiency integrated OLED panel manufacturing processes.
- OLED materials manufacturing should also be supported. Organic molecule production needs exploration to reduce the material cost and drive bulk volume.
  - Furthermore, the quality of substrates and electrodes are important as it affects yield. These materials need to be produced at lower cost but not forsaking quality.
- OLED deposition equipment needs prioritization as well. High throughput and high material utilization are important for panel manufacturing.
- The use of repurposed equipment could serve as a stepping stone towards reducing costs. The profits generated from this equipment could be invested in upgraded equipment.

7. **DOE Soapbox**
Mark Taylor, Corning Incorporated
- Corning is in the process of developing flexible glass which will enable high performance electronic devices made by continuous low cost processes.

    - Flexible glass has good reliability in both manufacturing and use. It is also very strong at the surface; however the edge strength is minimal so edge tab protection is under development.
- Product samples are currently available for sheet glass up to 250mm by 300mm and spooled glass 10m long and up to 300mm wide. By mid 2012, Corning expects to have spooled glass and sheets up to one meter wide available as well.
- Flexible glass offers important potential benefits for OLED lighting, but there are still issues that need to be addressed.
    - Corning has a thickness target for flexible glass of 100microns which would enable flexibility for roll to roll processing and for luminaires.
        - However, roll to roll technology on flexible glass still needs to be developed specifically for OLED technology.
    - Another benefit is its effectiveness as an oxygen and water barrier which would eliminate the need for barrier coatings.
        - Work still needs to be done on edge sealing.
    - Flexible glass also offers a pristine surface making it an ideal substrate for TCO.
        - However, advancements in low roughness TCO and roll-to-roll process technology are still needed in order to take advantage of this benefit.
    - The product also is highly transparent leading to low optical losses.
        - Light extraction on a manufacturing basis still needs advancement.

8. 2012 Manufacturing Roadmap OLED Roundtable
Florian Pschenitzka, Cambrios Technologies Corporation

- Task M.O3 is the most important priority. Support for low cost integrated substrates is of particular importance.
- The current cost for polished ITO at 10 ohms/square is about $200/m^2. Integrated substrates are much more expensive.
- The glass substrate, light extraction layer and TC electrode (e.g. ITO) are the main cost components.
- Cambrios is working on developing silver nanowires to replace ITO.
- Potential technologies for lower costs include the following:
    - Slot-die wet coating which has a lower cost of ownership than sputtering.
    - For patterning, screen printing and slide coating are widely used in the touch panel industry and has proven to be reliable, scalable with high throughput and a low cost of ownership.

9. Manufacturing Strategies for OLED Cost Reduction
Jim Dietz, Plextronics

- LED adoption was very slow from the early 1990's until just a few years ago when displays began using LED technology. The display industry had higher adoption than general illumination which led to the acceleration in adoption of LEDs for lighting.
- The rate of adoption for OLED lighting products will increase significantly if OLED lighting manufacturers can leverage the expertise gained from the large area display industry.
- In order to increase adoption OLED manufacturers need to increase volume and decrease variable cost. Ultimately, the industry needs to adapt a low capital expenditures model.
- Currently, Plextronics is working to understand thin film defects in devices and is seeking to collaborate with others on defining process flows and setting key performance indicators.
- Collaboration needs to be industry-wide. As an industry it is necessary to development metrics and targets for manufacturing productivity.
- Tasks M.O2 and M.O3 should be prioritized and funded by the DOE.

  - M.O2: collaboration is needed to increase throughput and yield. Improving equipment uptime is also important.
    - In addition to process development, focus should be placed on moving towards representative manufacturing processes and facilities.
    - The development of a center where manufacturers can work together to drive process development (i.e. SEMATECH) is needed.
  - M.O3: Improving substrates and encapsulation is also required to reach low cost targets.

10. DOE SSL Manufacturing – OLED
Thomas Albrecht, EMD Chemicals

- Task M.O1 should be the leading priority.
- DOE should foster collaboration between panel manufacturers, equipment suppliers and material makers to ensure compatibility of all systems.
- Furthermore, stacks need to be manufactured in up to date equipment. To show true progress in manufacturability, equipment should be demonstrated on several relevant emissive layer formulations.
  - Typically, utilization and speed are demonstrated on NPB and AlQ due to their availability and low relative costs. However, these materials are not relevant for the OLED stacks of the future.
  - NPB and AlQ do not have the sensitivity or instability of some of the newer OLED materials, particularly those in the emissive layers.
- A standard stack needs to be developed because it would enable true equipment comparisons between various equipment suppliers and makers. The standard stack should incorporate:
  - HIL.
  - HTL (preferably with a higher glass transition temperature than NPB).
  - Representative hosts for Red/Green/Yellow and Blue.
  - Triplet dopants.
  - ETL (preferably with some type of n-doping (Li or other)).
- In the long run, solution deposition processes are the key. This will be pivotal to reducing costs.
  - EMD Chemicals is currently making progress with soluble small molecules which are easier to purify.
  - More cooperation is needed between panel maker, equipment maker and material maker to develop suitable ink formulations.
  - Solvents and additives for ink formulation impact device performance and inks must be custom formulated for different deposition methods.
- Several suggestion were made for refining priority M.O1:
  - Verbiage should be added to indicate that equipment must be demonstrated on several relevant emissive layer formulations (VTE or VTE-like solutions).
  - Equipment manufacturers should collaborate with OLED panel and material manufacturers.

11. Nick Colaneri, ASU

- At Arizona State University's Flexible Displays and Electronics Center the focus is on accelerating industry activities.
- Encapsulation is a common problem associated with making flexible displays. Both display and lighting products have the common need for barrier/encapsulation. However, in the long run, OLED lighting product costs will be dominated by the substrate.
- Reducing substrate costs is not a physics problem but rather a manufacturing/engineering issue.
  - To reduce costs, equipment throughput must increase and process time must decrease. Ultimately, substrate costs must be reduced to \$100 – \$300 per gram.

- There are several potential alternatives to the current substrate methods:
    - Multilayer thin films.
        - In order to get effective barriers several organic and inorganic layers are necessary which increases costs. Can the number of layers be reduced?
    - Atomic layer deposition/deposited thin films.
        - If time is not a concern you can deposit an extremely thin impermeable film, but this will never be a low cost process.
    - Other monolithic thin film deposition processes (e.g. PECVD).
    - 3M barrier film.
    - Roll to roll processable thin glass.

12. Top Emission OLEDS for Lighting
David Gotthold, PNNL

- Currently working on understanding manufacturing challenges for thin films, they have revisited top emission which offers several advantages.
    - One advantage is leveraging the display industry; the amount of money that is being spent on lighting is negligible compared to the display industry. Leveraging top emission displays will provide the benefits of:
        - Proven manufacturing processes and equipment.
        - Economies of scale.
        - Device/material development.
        - Patterning for tunable color.
- Top emission also enables opaque substrates which allows for metal or (thick) polymer substrates using roll to roll processing, hence providing better thermal management and simpler mechanical handling.
- There are certain challenges accompanying top emission lighting that are not present in top emission displays. Two of these primary issues are current distribution over a large area and broad spectrum light extraction.
    - Several manufacturing developments are also necessary for top emission, these include:
        - A TCO/conductive layer that can be deposited in large areas on organic layers with good conductivity and yield.
        - Low cost easily printable bus lines that can be deposited and patterned on top of the active layer.
        - Light extraction with color uniformity to mitigate microcavity effects.
        - Low cost encapsulation, particularly for flexible applications.
- Multi-step integration for manufacturing is another important area in order to reduce cost, complexity and improve yield. Enabling cross collaboration across technology sets will also be a huge benefit.
    - This could include combining substrate smoothing and HIL, TCO and lighting extraction or encapsulation with light extraction and the desiccant.
- Improving metrology and process control is also important. An optical tool for simple, reliable, and fast process feedback for production control is needed.
    - Evaluating which process parameters are critical to volume production and which process parameters can be seen optically during processing (i.e. emission/absorption spectra, surface morphology, film thickness) are also critical for improving OLED manufacturing.

13. **Addressing Scaling Requirements for Efficient OLED Manufacturing by Organic Vapor Phase Deposition**
    Rainer Beccard, AIXTRON
    - There are several targets or objectives that must be met to make high throughput OLED manufacturing technology cost effective:
      - Material utilization efficiency of over 70%.
      - Cycle time of less than 90 seconds.
      - Thickness non-uniformity less than 2%.
      - Product performance consistency.
        - Reproducibility is a big issue.
    - AIXTRON is analyzing how scaling up affects organic source requirements. Scaling up requires dramatic increases of source evaporation capacities. Even though efficiency goes up with larger areas, there is pressure on achieving sufficient deposition rates for the source.
      - Therefore high efficiency with a very high feed rate is needed to achieve the necessary deposition rates.
      - There must also be a certain level of flexibility. The equipment must be able to have a wide range of deposition rates.
    - AIXTRON has also been looking into reducing the cost and footprint of tools by processing multiple stacks and combining process steps.
    - There is a need for more integrated systems even at the R&D scale.

14. **Coating Equipment from R&D to Full Production**
    Miguel Friedrich, nTact
    - One of the major challenges of OLED manufacturing is the cost of equipment, especially R&D systems.
    - Last year nTact launched two products specifically geared for R&D approaches. One was a table top lab solution that allows slot-die solution-based coating. This equipment system costs under $100k while providing good performing product.
    - This R&D extrusion coating system is capable of:
      - Depositing a wide range of materials.
      - Good coating uniformity (roughly under 5% uniformity).
      - High process material utilization.
      - Small system footprint.
      - Processing in fully inert environment.
      - Proven scalability to high volume production and applicable to roll to roll processing.
        - Up to now the main focus has been on the use of HIL and HTL but other potential material applications could be developed to lower costs.
    - nTact has also been further developing selective coating and macro patterning techniques.
      - They have developed a method for depositing multiple arrays of well-defined, rectangular shapes on a single substrate.
    - The ultimate goal is to be able to provide an R&D platform that is directly scalable to mass production equipment.
      - However, there is a need for collaboration between equipment manufacturers and material suppliers. This collaboration would help to improve equipment performance and lower costs.

15. **DOE Roundtable Slides**
    Tom Trovato, Trovato Mfg. Inc
    - Currently, Trovato Manufacturing focuses on the development of OLED research tools. However, it is important that research funding be dedicated to the development of tools for high

volume OLED production. Manufacturing OLED production systems in the U.S. will help create more jobs domestically.
- In addition, the majority of these research tools are being exported to Asian markets. Since OLED SSL is a global industry and the majority of OLED progress has been in Asia, the U.S. should focus on providing Asian markets with the equipment they need to begin mass producing OLEDs.
- In general the U.S. should focus on business plans that will enable it to contribute to the global OLED market.

16. Challenges and Solutions for Thickness Control of OLED Thin Films
Scott Grimshaw, COLNATEC

- There are several process control challenges in OLED manufacturing:
    - Films are often <10nm thick and thus difficult to measure in continuous processing systems.
    - Substrates are also very large and push the limits of measurement systems.
    - Organic thin films vary in structural morphology and cause erratic thickness measurements.
- The sensing technology currently available for measuring film thickness fails too quickly and has several imbedded errors.
- Colnatec has developed solutions to some of these process control problems:
    - Self-cleaning thickness sensors for the monitoring continuous production processes over 200+ hours.
    - Sensors that can measure organic thin films with high accuracy (< 1 angstrom).
    - Sensors that do not have rate noise during deposition.

DOE OLED Roundtable Participants

Thomas Albrecht	EMD Chemicals
Rainer Beccard	AIXTRON
Michael Boroson	OLEDWorks LLC
Nick Colaneri	Arizona State University
Jim Dietz	Plextronics
Miguel Friedrich	nTact
David Gotthold	Pacific Northwest National Laboratory
Scott Grimshaw	COLNATEC
Jerry Liu	GE Global Research
Jeff Meth	DuPont
David Newman	Moser Baer Technologies
Dennis O'Shaughnessy	PPG Industries, Inc
Florian Pschenitzka	Cambrios Technologies Corporation
Nikhil Taskar	WAC Lighting
Mark Taylor	Corning
Tom Trovato	Trovato Manufacturing, Inc