Solid State Lighting Program
Final Report

April 10, 2014

Creation of a U.S. Phosphorescent OLED Lighting Panel Manufacturing Facility

Period of performance: 4/15/2010 – 9/30/2013

Work Performed Under Agreement:
DE-EE0003253

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A. Project Summary

Universal Display Corporation (UDC) has pioneered high efficacy phosphorescent OLED (PHOLED™) technology to enable the realization of an exciting new form of high quality, energy saving solid-date lighting. In laboratory test devices, we have demonstrated greater than 100 lm/W conversion efficacy. In this program, Universal Display will demonstrate the scalability of its proprietary UniversalPHOLED technology and materials for the manufacture of white OLED lighting panels that meet commercial lighting targets. Moser Baer Technologies will design and build a U.S.-based pilot facility. The objective of this project is to establish a pilot phosphorescent OLED (PHOLED) manufacturing line in the U.S. Our goal is that at the end of the project, prototype lighting panels could be provided to U.S. luminaire manufacturers for incorporation into products to facilitate the testing of design concepts and to gauge customer acceptance, so as to facilitate the growth of the embryonic U.S. OLED lighting industry. In addition, the team will provide a cost of ownership analysis to quantify production costs including OLED performance metrics which relate to OLED cost such as yield, materials usage, cycle time, substrate area, and capital depreciation.

This project was part of a new DOE initiative designed to help establish and maintain U.S. leadership in this program will support key DOE objectives by showing a path to meet Department of Energy Solid-State Lighting Manufacturing Roadmap cost targets, as well as meeting its efficiency targets by demonstrating the energy saving potential of our technology through the realization of greater than 76 lm/W OLED lighting panels by 2012.

All Year I goals were successfully met on time, as highlighted below:

- ***Demonstrated white PHOLED pixel with efficacy = 72 lm/W, CRI = 85, and lifetime LT70= 55,000 hours at 1,000 cd/m²^2.***
- ***Demonstrated 150 mm by 150 mm large-area white PHOLED panel with efficacy = 66 lm/W, CRI = 79, and lifetime LT70= 12,000 hours at 1,000 cd/m^2.***
- ***Completed technology implementation package on PHOLED panel fabrication for Moser Baer Technologies.***
- ***Completed site selection, layout, equipment set and process flow for the manufacturing facility.***
- ***Developed cost of ownership model.***

The Year II goals are summarized below:

- ***Completed facility preparation and status update on equipment and vendor selection***
- ***Completed site acceptance of for the OLED deposition/encapsulation equipment at the vendor in Japan***
- ***First prototype panels produced by manufacturing facility.***

- ***Report describing panel performance, TACT time and yield produced by manufacturing facility.***

Under this project, the manufacturing facility was designed and the cleanroom established in NY State. The custom OLED deposition tool was designed and assembled ready for incorporation into the prototype manufacturing line. Unfortunately, additional funding beyond the program cost share could not be obtained, which resulted in MBT being unable to purchase the remaining manufacturing equipment necessary to setup and complete the prototype line.

B. Planned Goals & Milestones

In this work the team of UDC and Moser Baer Technologies (MBT) were to design and setup a U.S. based PHOLED pilot lighting manufacturing line. The Team will implement UDC's PHOLED technology in this manufacturing line, so that at the end of this program we could provide prototype lighting panels to U.S. luminaire manufacturers to incorporate into products to facilitate testing of design concepts and gauge customer acceptance.

The manufacturing technology for PHOLED lighting products was to be implemented in 3 constituent parts: i) substrate technology; ii) PHOLED technology and; iii) encapsulation technology. The proposed innovative manufacturing facility is based on the high throughput processing of 150 mm × 150 mm glass substrates using known and proven production methods. This accomplishes two of our key goals which are to lower the manufacturing cost without having to account for the risks associated with developing large unproven deposition equipment. Our strategy contrasts with the conventional approach of lowering production costs through the economies of scale associated with increasing substrate size.

In addition, The Team will provide a cost of ownership analysis to quantify production costs including OLED performance metrics which relate to OLED cost such as yield, materials usage, cycle time, substrate area, and capital depreciation.

<u>Phase 1 (Months 1 - 12) Technology and Facility Preparation Phase</u>

The objective of Phase 1 is to prepare a PHOLED panel technology package to ensure that the manufacturing facility is being designed to meet the performance requirements goals based on UDC's PHOLED technology, which includes efficacy, lifetime, total lumen output and product cost. This will include site selection studies to pick the most appropriate location for our manufacturing facility, a proposed layout and process flow for our manufacturing facility, staffing requirements, and a detailed cost of ownership analysis.

<u>Phase 2 (Months 1 – 36) Total Cost of Ownership Modeling</u>

The Team will develop a cost of ownership model OLED performance metrics and routinely used measurable metrics which relate to OLED cost such as yield, materials usage, cycle time, substrate area, and capital depreciation. This model will be used continuously throughout the project to monitor performance and track progress towards our goals.

Phase 3 (Months 7 - 24) Facility Implementation Phase

This Phase will be based around MBT ordering the necessary equipment for the manufacturing facility, installation to bring the equipment set online as individual process modules, and finally integrating the process modules to verify the overall production line. As part of this effort UDC will implement its PHOLED panel technology at the manufacturing facility.

Phase 4 (Months 7 – 36) Commercial Implementation

The objective of Phase 4 is to ensure commercial success by matching the panel production to the requirements of our luminaire customers and ensuring that the products meet our performance goals. We will also develop a commercialization roadmap to plan for future manufacturing facilities to provide a path for higher volume and lower cost products. Also included will be initial outreach to potential luminaire manufacturers who would be prospective customers from our facility.

Task List

Task I: **Project Management and Planning**
Task II: **Development of PHOLED Panel Technology Implementation Package**
Task III: **Pilot Manufacturing Facility Preparation**
Task IV: **Development and Implementation of Cost of Ownership Analysis**
Task V: **Production Facility Implementation**
Task VI: **Technology Implementation**
Task VII: **Commercial Implementation**
Task VIII: **Commercial Roadmap for Higher Volume, Lower Cost Production**

C. Year I and II Accomplishments: Progress against Milestones

Table below shows milestones, deliverables and their final status, as compared to the program plan.

Table 1. Summary of milestones, deliverables and final status, as compared to the program plan.

Phase 1	Description	Date	Final Status
Milestone 1	Results of PHOLED panel demonstrating 60 lm/W and CRI >80 at 1,000 cd/m^2	Jan 15th, 2011	Completed on time
Milestone 2	Technology implementation package	Apr 15th, 2011	Completed on time
Milestone 3	Site selection, layout, equipment set and process flow for the manufacturing facility	Jan 15th, 2011	Completed on time

Phase 2			
Milestone 4	Total cost of ownership model	Jan 15th, 2011	Completed on time
Phase 3			
Milestone 5	Status update on facility, equipment set and vendor selection	Oct 15th, 2011	Completed on time
Milestone 6	First prototype panels produced by manufacturing facility	Mar 15th, 2013	
Phase 4			
Milestone 7	Panel performance, TACT time and yield produced by the manufacturing facility. Cost of ownership projections versus performance	Apr 15th, 2013	
Milestone 8	Commercial roadmap for higher volume, lower cost future manufacturing facilities	Apr 15th, 2013	

Milestone 1: Results of PHOLED panel demonstrating 60 lm/W and CRI >80 at 1,000 cd/m^2
Due Date: Jan 15th 2011
Current Status: Completed
We demonstrated 150 mm by 150 mm large-area PHOLED panel with 66 lm/W power efficacy and CRI of 79.

Milestone 2: Technology implementation package
Due Date: Apr 15th 2011
Current Status: Completed
We successfully completed the technology implementation package for Moser Baer to enable the pilot manufacturing facility to fabricate state-of-the-art PHOLED structures.

Milestone 3: Site selection, layout, equipment set and process flow for the manufacturing facility
Due Date: Jan 15th 2011
Current Status: Completed
Infotonics Technology Center (ITC) in Canandaigua, New York was selected as the factory site. Preliminary facility layouts started June 2010, and process flow was defined April 2010. Schedule for the OLED deposition equipment design to meet cost targets and subsequent assembly has meant a six month delay to the original schedule.

Milestone 4: Total cost of ownership model
Due Date: Jan 15th 2011
Current Status: Completed
Developed cost of ownership model based on the initial process and extended the model to predict costs based on two more efficient processes.

Under this project, the manufacturing facility was designed and the cleanroom established in NY State. The custom OLED deposition tool was designed and assembled ready for incorporation into the prototype manufacturing line. Unfortunately, additional funding beyond the program cost share could not be obtained, which resulted in MBT being unable to purchase the remaining manufacturing equipment necessary to setup and complete the prototype line.

D. Description of Work Performed under the Contract – Year I

Task I: Project Management and Planning

In December 2010 the program was extended for an additional six months (at no cost) to account for additional time required to design and build the OLED deposition manufacturing equipment to meet the required cost targets.

Phase I Technology and facility preparation

PHOLED panel technology

We have designed our two-EML layer white PHOLED device structure to achieve high efficacy, high CRI and long lifetime, as illustrated in Figure 1. This structure comprises low voltage transport layers and low voltage host materials. All emissive materials are phosphorescent, enabling close to 100% internal quantum efficiency (IQE). In particular we have recently improved the performance of the ETL layer – this has increased efficacy by 15-20%, depending on the specific device structure. This combination of low voltage and high IQE enables high power efficacy. Using this device stack, we fabricated white PHOLED pixel with area of 0.02 cm^2, and achieved power efficacy of 72 lm/W, CRI 85, and 55,000 hours life time at 1,000 nits. Table 1 lists all the performance specs for the white PHOLED pixel.

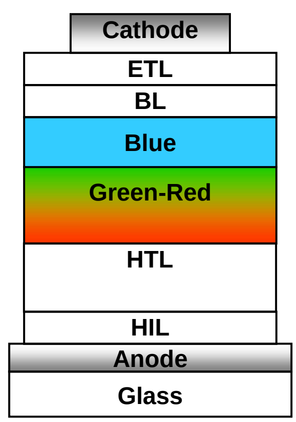


Figure 1: Device structure for two-EML layer OLED device (2010).

Table 2. Performances of white PHOLED pixel using device stacks from Figure 1.

	White PHOLED Pixel
Efficacy	**72 lm/W**
CRI	**85**
Luminance	1,000 nits
EQE	42%
Voltage	3.8 V
1931 CIE	(0.471, 0.420)
CCT	2810 K
Outcoupling Enhancement	2.12x
LT70 [hrs]	**55,000**

The above OLED device architecture was then transferred to 150 mm by 150 mm large-area OLED light Panel 1. As can be seen in Table 2, at 1,000 cd/m^2, we have achieved power efficacy of 58 lm/W from Panel 1. Data includes 1.75x efficacy enhancement achieved using an index-matched light extraction block. When the panel is operated at 1,000 cd/m^2, luminous emittance is about 2,600 lm/m^2, which is sufficient for initial commercial lighting products. EL spectra were measured inside an integrating sphere equipped with an Ocean Optics spectrometer. The integrating sphere collects light emitted from the lighting panel averaged over all angles inclusive of light extraction enhancement. Upon initial illumination at 1,000 cd/m^2, the lighting panel has CIE 1931 (x, y) = (0.466, 0.413) with CRI = 82 and CCT = 2640 K, which closely matches Energy Star chromaticity requirements of Solid State Lighting Luminaires. Lifetime of this panel reached LT70 = 30,000 hours.

EL spectra were measured upon initial illumination and again after lifetest to LT80. Emission spectra are shown in Figure 2. There is negligible color shift with aging, with duv = 0.001 at LT80. This exceptional color stability is achieved using our highly stable light blue phosphorescent materials system in our simple two-EML layer PHOLED stack. In addition, owing to our optimized panel layout, brightness uniformity across the panel after aging to LT80 is 89%.

Table 3: Performance of 150 mm × 150 mm phosphorescent OLED light panel. Data are presented at 1,000 cd/m^2 inclusive of 1.75x light extraction efficacy enhancement. Lifetime data is extrapolated from higher luminance using an acceleration factor AF ≈ 1.6.

Panel Metric	**Panel 1 [at 1,000 cd/m^2]**
Accomplish Date	Dec. 15th, 2010
Area	150 mm x 150 mm
Efficacy [lm/W]	58
Luminous Emittance [lm/m^2]	2,600
Voltage [V]	3.8
CRI	82
CCT [K]	2640

CIE 1931 (x, y)	(0.466, 0.413)
Brightness Uniformity after Aging to LT80	89%
Color Shift with Aging (duv at LT80)	0.001
Surface Temperature [°C]	20.7
Light Extraction Efficacy Enhancement	1.75X
Lifetime (LT70) [hrs]	30,000

By incorporating a higher efficiency red phosphorescent emitter (developed by UDC outside of this program), we fabricated 150 mm by 150 mm large-area white PHOLED light panel 2 (see Figure 2), and were able to achieve higher power efficacy of 66 lm/W at 1,000 nits with an 2.06x outcoupling enhancement by using a light extraction block. Table 3 lists the specs of Panel 2. This panel achieves a high CRI of 79 and CIE of (0.415, 0.438).

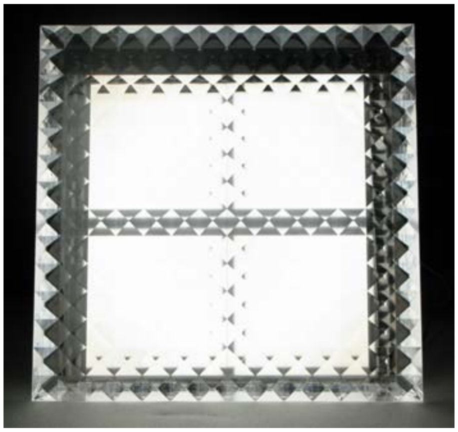


Figure 2: Image of white PHOLED light Panel 2 with light extraction block on top.

Table 4. Performances of 150 mm × 150 mm white PHOLED light Panel 2.

Panel Metric	Panel 2
Accomplish Date	Jan 15^{th}, 2011
Area	150 mm x 150 mm
Efficacy [lm/W]	66
Luminous Emittance [lm/m^2]	2,960
Voltage [V]	3.74
CRI	79
CCT [K]	3650
CIE 1931 (x, y)	(0.415, 0.438)
Light Extraction Efficacy Enhancement	2.06x

Table 4 lists the performances of both Panel 1 and Panel 2 against project goal. Panel 1 meets the CRI and lifetime target, and the power efficacy of 58 lm/W is very close to the efficiency target. Panel 2 achieved high power efficacy exceeding 60 lm/W, and a high CRI close to 80. The lifetime of panel 2 reached 12,000 hours.

Table 5. Performances of both 150mm × 150mm OLED light Panel 1 and Panel 2 compared to project goal.

Panel Metric	Goal	Panel 1	Panel 2
Accomplish Date	Jan 15th, 2011	Dec. 15th, 2010	Jan 15th, 2011
Area	150 mm x 150 mm	150 mm x 150 mm	150 mm x 150 mm
Efficacy [lm/W]	> 60	58	66
CRI	> 80	82	79
Lifetime (LT70) [hrs]	> 10,000	30,000	12,000

Technology Implementation Package

We completed the technology implementation package on PHOLED panel fabrication for Moser Baer Technologies by Apr 15th 2011, and met Milestone 2 on time. This document sets forth a procedure to make an organic light-emitting panel (OLED) that has been built on a rigid glass substrate. It will provide the process details used at UDC for initial substrate cleaning and organic device fabrication, encapsulation and test. In general, the document covers the following critical steps during OLED fabrication:

1. Substrate pre-treatment conditions prior to deposition of the organic layers

For large-area panels, the plate cleaning process is important because most of the potential shorting or degradation comes from particles, chemical residuals or other contamination left on the substrates during the cleaning. The substrate pre-treatment is required to be completed in class 100 clean room to ensure the least particle or moisture that may be stored onto the substrates. Certain types of chemicals are needed for cleaning the substrates, and as well as high-temperature baking to remove moisture. For large-area lighting panels, photo lithography is commonly used to form certain patterns onto the electrodes. Therefore, an inspection is essential to ensure substrates are well patterned into designated shapes.

2. High vacuum system set-up including source loading procedures etc.

The vacuum system should be in clean room environment to keep material sources particle free during loading. Organic materials should be outgassed prior to making devices. A dummy run or testing run may be applied after the source is loaded to stabilize the material. Sources needs to be refilled or replaced when it is in low level or whenever necessary.

3. Deposition conditions for the individual organic and metal layers

Deposition system should be in clean room environment to prevent the substrates from acquiring particles during loading. An integrated nitrogen glove box is connected to the OLED deposition system which has low humidity and oxygen level. Substrates or completed devices can be temporarily stored in the glove box. The OLED deposition tool should be kept under low pressure.

4. Encapsulation procedures to ensure long lifetime

Encapsulation is essential for OLED devices as organic materials degrade very fast when exposed to moisture or oxygen. The encapsulation requires cover glass, adhesive glue, desiccants and etc. The encapsulation procedure should be completed inside the glove box to prevent the organic materials from exposing to air. Once encapsulated, the device can be taken out of the glove box and stored in air condition.

The final completed full document includes the following steps:

- Substrate cleaning
- Crucible cleaning and staging
- Source loading and outgassing
- Substrate preparation prior to OLED growth
- Device fabrication
- Device encapsulation
- JVL-EL measurement
- Safety consideration

During each step, related materials and equipment are listed as well. OLED device structures transferred in this package are UDC's standard 2 band and 3 band EML white structures. Performances of these two types of devices have been reported last year. The encapsulation technique uses a cavity glass cover with two perimeter sealants and a desiccant. Most of the JVL measurements at UDC are conducted using standard testing samples. The testing samples are 2 mm^2 devices and the results will be analyzed to predict the large-area panel performances. Sample layout is shown in the document and the measurement procedure, including instrument calibration, is described step by step. In addition, the limitation of external quantum efficiency (EQE) calculation and the advantage of employing a Si Photodiode (PD) based detector are explained.

<u>Site selection, layout, equipment set and process flow for our Manufacturing Facility</u>

Site selection was completed in March 2010. We selected a 10,000 sq.ft location at the Infotonics Technology Center (ITC) in Canandaigua, New York (see Figure 3). ITC is a New York State Center of Excellence in Photonics & MEMS technology. A 6-inch semiconductor fab for MEMS and a microelectronic packaging facility were already in operation at the ITC location. The OLED lighting pilot facility could therefore use several "in-house" analytical capabilities & technical staff competencies. The 10,000 sq.ft space will be built out into a cleanroom that will contain the OLED pilot manufacturing operations. We defined the process flow, as shown in Figure 4. The preliminary facility layouts started in June 2010, and are shown in Figure 5. Other accomplishments include:

- Pilot Line Requirements Document Completed July 1, 2010
- Cleaning system estimate received October 4, 2010
- Organic deposition and encapsulation system specifications completed October 19, 2010
- Manufacturing schedule and Acceptance Test Criteria for the Organic deposition and encapsulation systems completed November 29, 2010
- Purchase Order released for the longest lead systems, Organic deposition and encapsulation, November 30, 2010

Figure 3: Image of the selected site Smart System Technology and Commercialization Center (STC) in Canadaqua, NY.

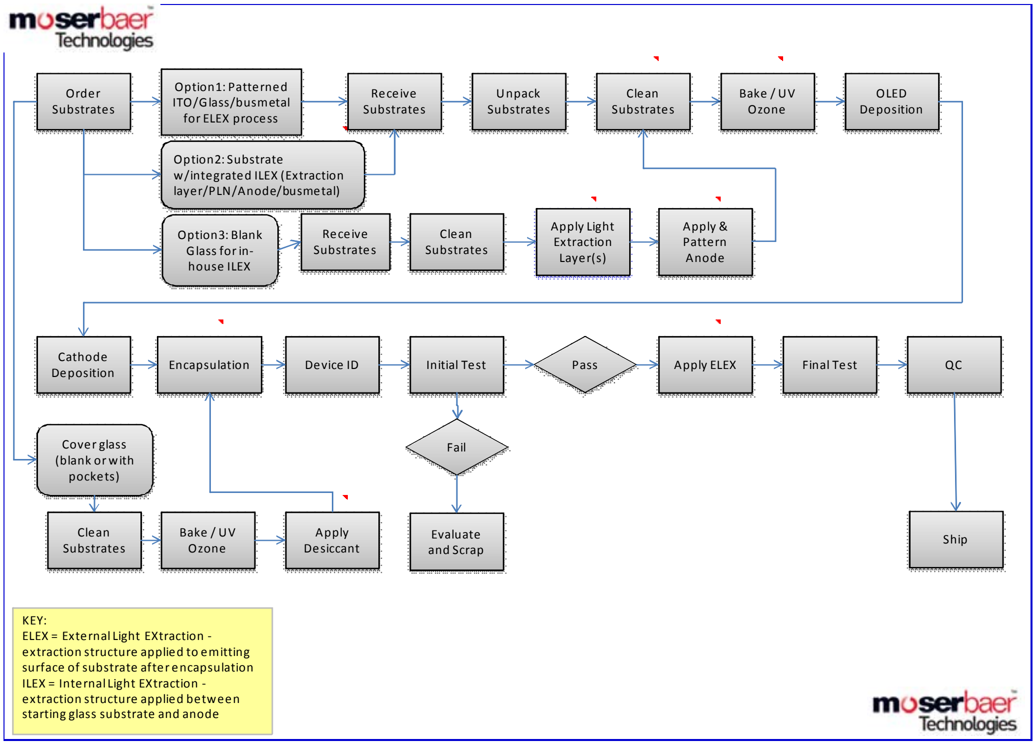


Figure 4: Preliminary process flow for manufacturing facility.

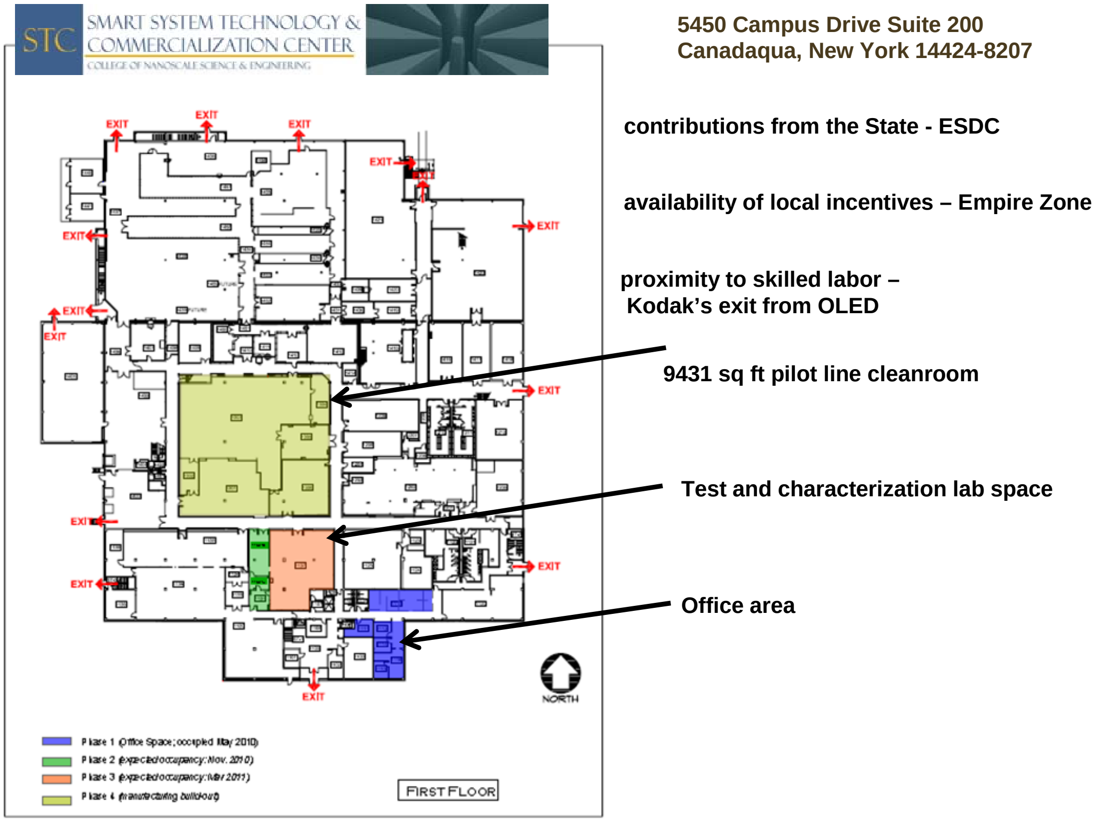


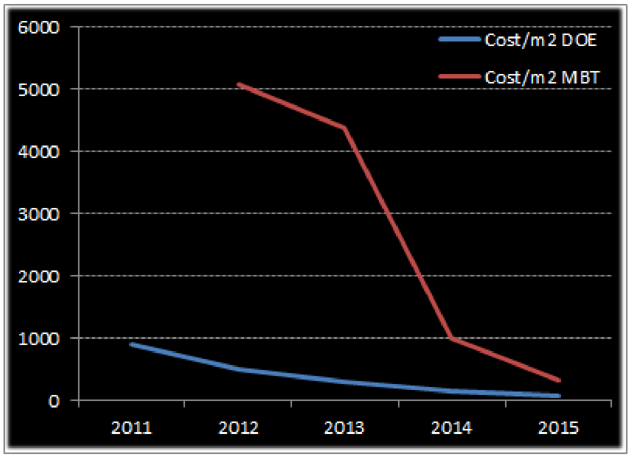
Figure 5: Preliminary facility layouts.

Phase II Development and Implementation of Cost of Ownership Analysis

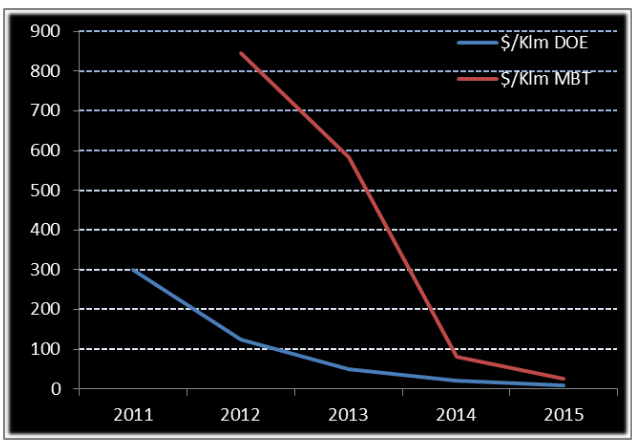
During Year I, we accomplished the following:

- Developed Cost Model to include:
  - 13 Worksheets
  - 10 Unique Process Flows
  - Step by Step Process Simulation showing capital, depreciation, space, component and material costs
  - Provided two cost outputs:
    - Panel Costs by cost element
    - Fixed and Variable Costs
- Collected preliminary material, component and capital costs from Universal and Moser Baer. (The preliminary nature of some costs are due to the lack of actual cost information because of the early stage of the project)
- Ran the Model to test its validity, made changes to for the revised timing of the project and the conversion from a 6-up wafer solution to the current 1-up wafer solution
- Added a process to account for sputtered cathode

- Produced Cost data for three scenarios:
  - Glass with patterned ITO, patterned grid, evaporated cathode and external light extraction layer
  - Glass with patterned ITO, patterned grid, evaporated cathode and internal light extraction layer
  - Glass with patterned ITO, patterned grid, sputtered cathode and internal light extraction layer



(a)



(b)

Figure 6: Roadmap of cost with respect to (a) area ($/m^2) and to (b) light output ($/klm) based on our cost analysis.

Our project has been designed to reduce the cost for OLED solid-state lighting. Our innovative strategy for cost reduction is to use the high throughput processing of 150 mm × 150 mm substrates, as opposed to the conventional approach of high capital investment associated with large size (Gen 2 or Gen 4) OLED deposition equipment. Figure 6 shows the roadmap of cost with respect to area (Figure 6a.) and to light output (Figure 6b.)

based on our cost analysis, how we achieve significant cost savings, and how we can approach DOE cost targets. We found that:

- Cost Model trails DOE roadmap while production is 5,000 wafer / month but begins to catch up at 100,000 wafers / month;
- Increasing the wafers / platter from 1 to 4 or 6 could significantly reduce costs.

Phase III Facility Implementation

The purchase order for the longest lead systems (OLED deposition tool) included a commitment to a delivery schedule. Using this schedule we worked to synchronize the construction of the cleanroom space and the purchase of the remaining process and support equipment. Work started on the requirements documentation for the factory space. We had resources in place to interface with the engineering firm and are exploring a number of potential grants and economic incentives to help offset the factory construction costs.

We formally engaged the architectural design firm in January 2011. The first item addressed was to audit the available utility resources and identify the gaps and long lead items such as additional electrical power, gas and water requirements. We followed this with a detailed space requirements document for the cleanroom construction using updated data from the equipment supplier. The plan is to partition the approximately 9500 square feet of space into class 10,000, class 1000 and class 100 mini environment sections. The goal was to design the space with long term utility savings in mind by not overdesigning the clean space.

Preliminary source evaluations started with the metrics being temperature, rate, film uniformity and degradation profiles of the materials. This work was to lead to the final configuration of the sources in the organic deposition system.

<u>Production Facility Preparation</u>

The Preliminary Project Scope for the cleanroom build out was completed in Year I. The outline of the scope of work details the demolition and renovation work for the architectural, mechanical and electrical requirements of the cleanroom space. This deliverable includes a detailed utility matrix defining flow rates and pressures for everything including domestic and DI water, steam, process gasses, house vacuum and clean dry air. The primary electrical requirements and recommended distribution is defined and HVAC equipment details are included. We prepared to enter the next phase of the cleanroom design and renovation, are finalizing the lease agreement and will prepare bid packages for the construction firms.

The Japanese supplier of the deposition and encapsulation systems report that they were still on schedule to ship the systems in early November in spite of the ongoing issues surrounding the March 11, 2011 earthquake. We met the milestone of having the facility design completed in May and believe the build out and commissioning of the cleanroom will be completed on schedule at this time.

1. Glass Cleaning System:

As a result of the meeting held on Mar 30, 2011 between the SMIF (Standard Mechanical Interface – a module used to transport sensitive organic structures between various process systems) and the cleaner suppliers in Japan, new options for the handling of the substrate between the cleaner and several potential solutions to the moisture bake out challenge were identified. These concepts were evaluated with the expectation that we will design enough flexibility into the material handling options to allow the evaluation of these options in parallel.

2. OLED Deposition System:

A formal design review with the equipment supplier was held at the MBT site for this and the encapsulation system on February 16th and 17th, 2011. Detailed drawings showing our proposed equipment positioning in the factory including the roughing and high vacuum pump locations, the electrical interconnect, gas supplies and control panel locations were reviewed by the equipment supplier. After incorporating their suggestions, we now have a facility layout that will minimize noise and heat load in the clean space as well as provide a very good material/process flow solution.

3. Sputtered Cathode Deposition System:

Representative equipment specifications for this future system were compiled from several potential sources and both space and utility requirements have been reserved and integrated into the facility design.

4. Encapsulation System:

The design review identified a few new utility requirements that were added to the facility utility matrix and cleanroom requirements documentation. After reviewing our layout proposal, the supplier had a small number of suggestions to further optimize the cabling and plumbing routing for this system. We are still discussing the optimal control panel location but all other issues have been resolved and this system is on schedule.

Dr. Jan van den Brink and his team of scientists in Eindhoven/Netherlands are working on R&D for light extraction technology. They are preparing to expand their work to include fabricating panels with UDC materials and experiments with desiccant and edge seal options. The plan includes using a manual fixture that simulates the encapsulation process we will use in the automated system. Discussions with the equipment supplier to supply the fixture continue in the following months.

5. Test and support equipment:

We requested quotations for the life test equipment and the responses were mapped to a decision matrix. Following is an excerpt from the decision matrix used to down select to the supplier of choice for the "fade" (life test) system. Detailed discussions where we will share panel design details and negotiate the final system configuration and cost under a non disclosure agreement started in June, 2011.

Table 6. Excerpt from the decision matrix used to down select to the supplier of choice for the "fade" (life test) system

Criteria	Weight
System Technical Capabilities	**0.70**
Support for product testing - new reqmt	
Sensor(s) (mono, color, spectral))	**0.25**
Temperature control (hot plate vs. TEC)	**0.20**
Constant luminance testing	**0.05**
Peak voltage/current per icon/DUT (200 mA min)	**0.30**
Customer tools (GUI, test monitor, LT extrap.)	**0.15**
Ease of Use (system configuration)	**0.05**
System Technical Capability Score:	**1.00**

Criteria	Weight
Quote Considerations	**0.30**
System cost (shipping, duties, etc)	**0.40**
Timely response (on-time quote) - ongoing support	**0.20**
Company experience/reputation	**0.25**
Footprint	**0.10**
Utility Requirements (chill water, electric, vent)	**0.05**
Install & Training - new reqmt	
Other Quote Considerations Score:	**1.00**

6. Miscellaneous and support equipment:

A formal request for proposal / quotation package was prepared to secure a dehydration / bake solution for the substrate and cap glass. Five potential suppliers were selected and packages were sent out. The plan was to evaluate each proposal against selection criteria similar to that used for the test equipment and choose a supplier to build this system. The expectation is that when we bring supplier up to speed some of the basic material handling building blocks developed for this system will be available to integrate into our future systems.

E. Description of Work Performed under the Contract – Year II

Milestones accomplished:

Milestone 5: Completion of facility preparation and status update on equipment and vendor selection
Due Date: Oct 15th, 2011
Current Status: Completed
The facility upgrades have been completed and the class 1000 clean room has been built and is operational.

Milestone 6: First prototype panels produced by manufacturing facility
Due Date: March 15th, 2013
Once the equipment has been installed, all the individual process modules will be exercised. Substrates will then be processed through the complete manufacturing facility to verify and optimize the integration of the individual process modules. Our goal is to have the first lighting panels produced by the facility by month 24 of the project.

Milestone 7: Report describing panel performance, TACT time and yield produced by manufacturing facility.
Due Date: April 15th, 2013
As production data is available from the manufacturing facility, we will update the cost of ownership model with OLED performance metrics and routinely used measurable metrics which relate to OLED cost such as yield, materials usage, cycle time, substrate area, and capital depreciation. This model will be used continuously throughout the project to monitor performance and track progress towards project goals.

Task I: Project Management and Planning

We continued to develop and maintain a Project Management Plan (PMP) throughout the course of the project. We have reviewed and updated the PMP at the end of each Budget Period and resubmitted as a part of the budget period continuation application. The PMP was modified on an ad hoc basis to reflect significant changes or deviations of planning.

Task II: Development of PHOLED Panel Technology Implementation Package

We completed Year I goal by demonstrating 150 mm × 150 mm large-area white PHOLED lighting panel, with a high power efficacy of 66 lm/W and a high CRI of 79. During Year II, we investigated improved device structure, panel design and outcoupling enhancement towards achieving the following goals:

Table 7. Year II program performance goals

Performance metric for PHOLED panel	Proposed under this program At Month 9 (Completed)	Proposed under this program At Month 24
Panel efficacy (lm/W)	60	80
Luminance (cd/m^2)	>1,000	>2,000
Lifetime (LT70) (hours)	10,000	20,000
CRI	>80	>80

During Year II we demonstrated a 19.11 cm^2 white PHOLED lighting panel with a high power efficacy of 75 lm/W and a high CRI of 83. A 6mm high index extraction block was used. A summary of this achievement is below.

Panel 19.11 cm^2	With Outcoupling
Efficacy [lm/W]	75
Luminance [cd/m^2]	1,000
CRI [Ra]	83
CCT [K]	2810
1931 CIE	(0.457, 0.419)
Duv	0.003
Efficacy Enhancement	1.63X
LT70	On going

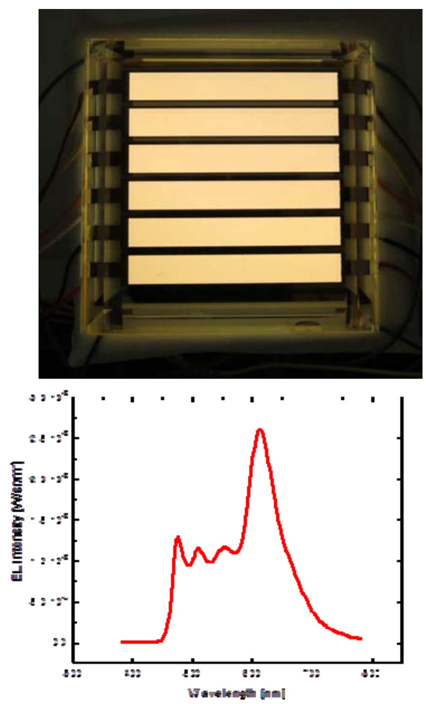


Figure 7: Performance summary for a 19.11 cm^2 white PHOLED lighting panel with a high power efficacy of 75 lm/W and a high CRI of 83

To achieve our final panel performance milestone for a 150mm x 150mm lighting panel (> 80 lm/W), an improvement in efficient light extraction from the OLED device will be required. We have examined several different light extraction methods. A summary of some of the techniques that have been reported to improve the light extraction are below.

1. Light extraction blocks

   In pervious DOE programs, we have reported about twofold enhancement of light extraction efficiency by adding a geometrically optimized acrylic block to the OLED devices. Figure 8 shows an example of OLED luminaire with a parabolic-curved light extraction blocks attached to the glass substrate. Light trapped in the substrate mode can be extracted from this approach.

Figure 8: An example of OLED luminaire with light extraction blocks.

2. Surface scattering layers

   Use of micro-lenses on the backside of the glass substrate is one of the most effective technique for extracting out substrate waveguided modes. In presence of ordered micro-lenses on the surface (as shown in Figure 9), the angle of incidence of light rays is smaller than the critical angle that leads to light extraction and TIR light glass–air boundary is coupled out. It has been demonstrated that the light outcoupling can be improved using ordered micro-lenses by a factor of 1.5.

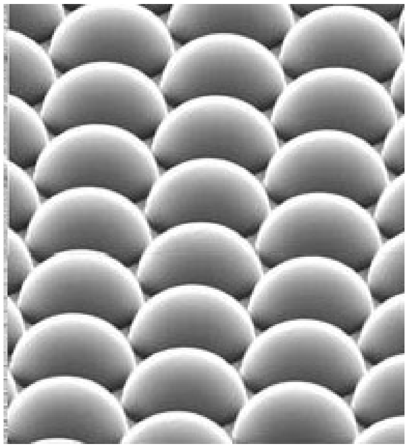


Figure 9: An SEM image of micro-lenses array.

3. Internal extraction layers

   Internal extraction layers can be inserted between ITO and glass substrate to couple out ITO/organic mode light. Figure 10 illustrates one of the ideas where a mixture layer with both high and low index materials is sandwiched between ITO and glass substrate. The high index material enables the light to travel from ITO to the internal extraction layer with minimum loss, while the low index material is preferably to have a dimension comparable to the wavelength of light so that light can be scattered out.

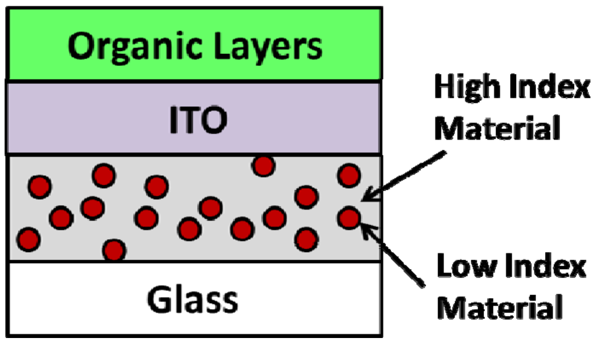


Figure 10: An illustration of OLED devices with internal extraction layers.

4. Low-index materials

   The low-index grid (LIG) redirects modes normally trapped within the high-index organic and indium tin oxide layers (waveguide modes) into the substrate where they can be further extracted into free space using methods such as microlens arrays or roughened surfaces. Figure 11 shows the illustration (left) and SEM image (right) of the OLED device embedded with LIG layer.

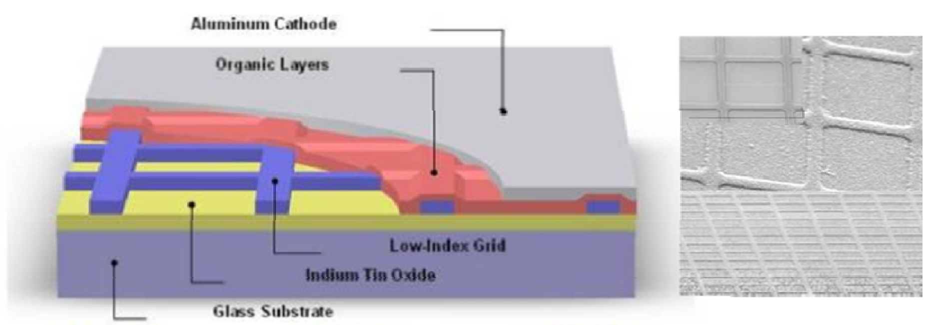


Figure 11: Illustration (left) and SEM image (right) of OLED device embedded with low-index grid.

5. High-index substrates

   High-index substrate can be used to replace normal glass (n = 1.5) to match the high index of ITO so as to extract light from ITO/organic mode. Additionally, high-index light extraction block with patterned surface can be combined to further couple out light trapped in the substrate mode. Figure 12 shows a pyramid surfaced light extraction block (left) and how it can be used to replace a conventional hemisphere shaped light extraction block.

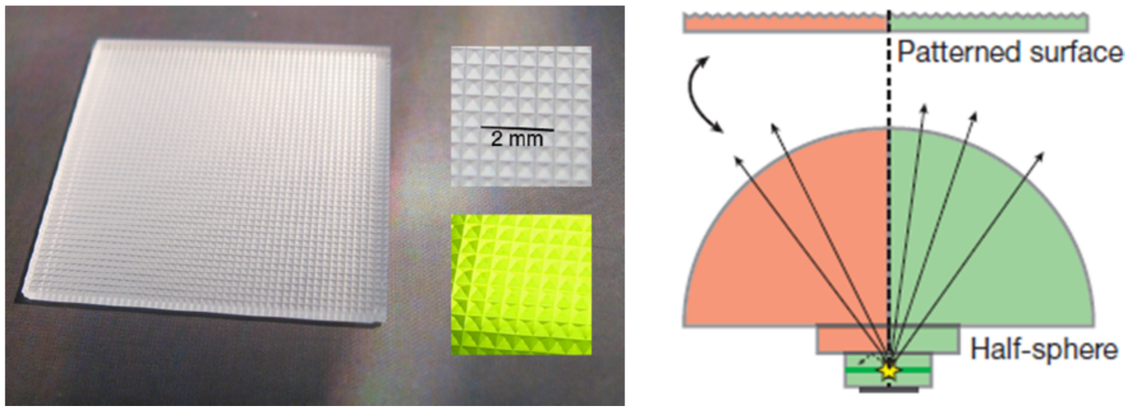


Figure 12: Employment of high-index substrate to extract light from ITO/organic layers.

Various techniques can be combined to maximize the external outcoupling efficiency. It is believed that > 2X light extraction efficiency can be achieved in a thin-form factor using the above approaches. These approaches, and some combinations of these approaches, are currently being evaluated and we expect to report new panel data in future reports.

We tested the performance of 2 outcoupling films on our PHOLED lighting panels. The first film is a commercial product made by Clarex. This film was 0.3 mm thick and the haze was 96%. This film is bonded and index matched to the substrate buy using a thermally curable, 2 part, optical cement. The second outcoupling film is a material that is under development from a Japanese company. The film is 0.1mm thick and the haze is 92%. This film has a PSA for bonding and index matching to the substrate. The PSA provides a simpler more manufacturable solution for attaching the film to the substrate. Once the release liner covering the PSA is removed, the film can easily be laminated onto the substrate by using a roller.

The films were tested on a 7.5 cm x 15 cm lighting panel using a standard white PHOLED structure. The lighting panels were operated at a current density of 5 mA/cm^2. We found that the Clarex film provided a 1.3X improvement in efficacy while the Japanese film provided a 1.4X improvement. The CRI was reduced for both films from 86 to 84. A summary of the results can be seen in the table below.

Table 8. Summary of the performance of 2 outcoupling films on our PHOLED lighting panels.

	OLED Panel	**OLED Panel + Clarex Film**	**OLED Panel + Japanese Film**
Emissive Area [cm^2]	**19.11 cm^2**	**19.11 cm^2**	**19.11 cm^2**
Enhancement		**1.34X**	**1.39X**
Luminance [cd/m^2]	2,180	2,930	3,050
Light Output [lm]	**13.11**	**17.61**	**18.30**
Voltage [V]	4.20	4.20	4.20
CRI (Ra)	**86**	**84**	**84**
1931 CIE	(0.446, 0.421)	(0.430, 0.421)	(0.428, 0.422)
Duv	0.0053	0.0077	0.0082
CCT [K]	2,990	3,260	3,290

Operating at J = 5 mA/cm^2

MBT developed both external and internal light extracting layers. Both of the extracting layers were tested on UDC PHOLED devices during the program.

The external light extracting layer was applied to our test substrate which consists of 6 stripes with and active area of 19.11 cm^2. The 2 band PHOLED structure was grown on the test substrates and tested at 2mA/cm^2 in a 20" integrating sphere, corresponding to approximately 1,000 cd/m^2. We observed a small shift in the CIE x direction for the devices with the EEL layer. The light enhancement from the EEL ranged from 1.27x to 1.38x. A summary of the results are below.

Table 9. Summary of the performance of MBT EEL on our PHOLED lighting panels.

Substrate #	Info	CIE x	CIE y	Output [Lumens]	Active Area [cm^2]	Voltage [V]	Enhancement
1	Control	0.432	0.413	5.65	19.11	3.82	1.00x
2	EEL plate	0.415	0.417	7.80	19.11	3.85	1.38x
3	Control	0.428	0.418	5.14	19.11	3.86	1.00x
4	EEL plate	0.409	0.420	6.53	19.11	3.85	1.27x
5	EEL plate	0.411	0.420	6.66	19.11	3.89	1.30x
6	EEL plate	0.411	0.420	6.65	19.11	3.88	1.29x

We reported on the initial testing for MBT's external extracting layer. The extracting layer was applied to our test substrate which consists of an active area of 6 stripes with and active area of 19.11 cm^2. We observed a small shift in the CIE x direction and a slight light enhancement for the devices with the EEL layer. We have grown test devices with MBT's internal extracting layer (IEL). The IEL was applied to our test substrate which consists of an active area of 1 cm^2. We also deposited our 3 band PHOLED structure on to the test devices.

Table 10. Initial performance results on our PHOLED lighting panels using MBT's IEL

ID	Info	CIE x	CIE y	Luminance [cd/m²]	Active Area [cm²]	Voltage [V]	PE [lm/W]	PE enhancement due to ILE
6-062712-4-3	Control (recipe A)	0.416	0.425	1016	1.00	4.09	39.0	
6-070312-3-3*	ILE plate (recipe A)	0.426	0.431	1070	1.00	4.12	40.7	1.04
6-062712-4-9	Control (recipe B)	0.410	0.420	803	1.00	4.16	30.3	
6-070312-3-8	ILE plate (recipe B)	0.441	0.416	956	1.00	4.15	36.2	1.20

These initial results show promise and the team will follow up to further investigate and characterize IEL performance.

Task III: Pilot Manufacturing Facility Preparation

Site selection was completed in March 2010. We selected a 10,000 sq.ft location at the Infotonics Technology Center (ITC) in Canandaigua, New York (see Figure 3). ITC is a New York State Center of Excellence in Photonics & MEMS technology. A 6-inch semiconductor fab for MEMS and a microelectronic packaging facility are already in operation at the ITC location. The OLED lighting pilot facility can therefore use several "in-house" analytical capabilities & technical staff competencies.

A class 1000 clean room was built and made operational. The clean room was certified and was measured closer to a class 100 clean room. A picture of the clean room is below.

Figure 13: A picture of the class 1000 clean room

Below is a scan of an exposed "witness plate" that was set out by our cleanroom certification vendor during their testing. The witness plate counts; show contamination that actually settles on the product. This helps to determine the product and room cleanliness, which in turn directly impacts yield. This data is a good baseline for comparison of settle-out contamination levels. This test will be repeated during equipment installation and line start-up.

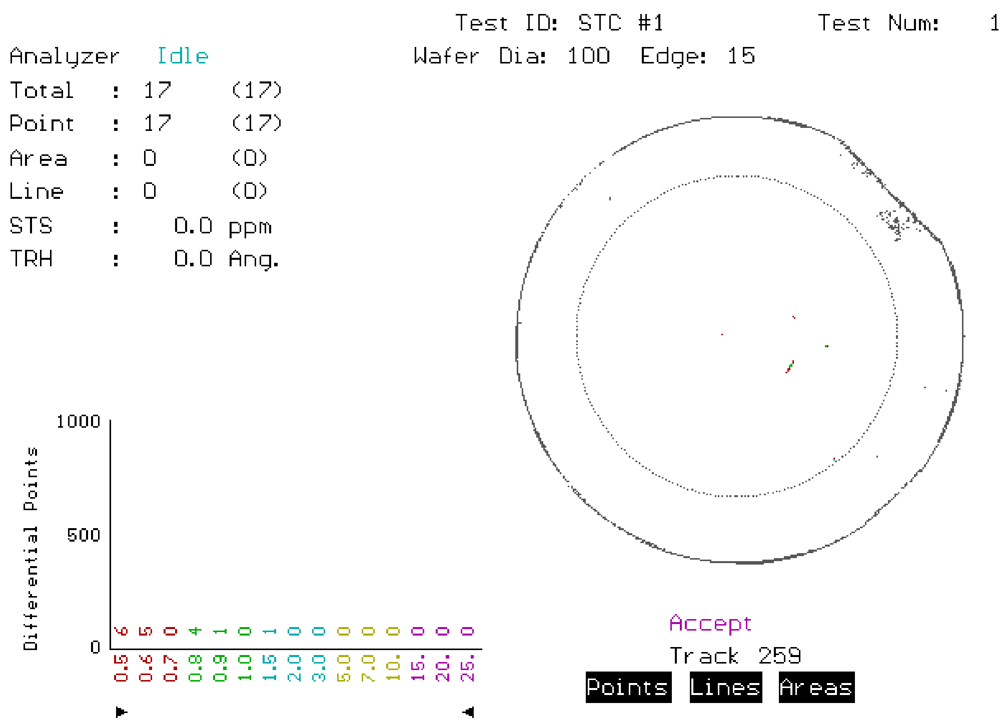


Figure 14: A scan of an exposed "witness plate" that was set out by our cleanroom certification vendor during their testing

Task IV: Development and Implementation of Cost of Ownership Analysis

During Year I, we established the cost model for ownership analysis. Further work on the model was focused on:

- Continue to validate the model
- Add cost and process changes as they become available
- Assist in developing other cost reduction opportunities

Task V: Production Facility Implementation

1. Glass Cleaning System:

A PO was issued for the glass cleaning equipment at the beginning of August 2011. Two engineers traveled to Japan to perform acceptance testing of cleaning equipment at the vendor's factory. The equipment passed all test criteria satisfactorily, with only a few minor issues that will be corrected before preparing the tool for shipment.

2. OLED Deposition System:

The site acceptance for the OLED deposition/encapsulation equipment at the vendor in Japan was completed.

3. Encapsulation System:

MBT made excellent progress on qualifying a lower cost encapsulation process which eliminates the most expensive component, the pocketed cover glass. This low cost encapsulation process was to be implemented at the startup phase of the pilot line.

4. Test and support equipment:

<u>OLED Lifetime Stability Station:</u>

An OLED lifetime stability station was completed and has passed testing.
Process monitor panels were obtained from OM & T which were used to test the system. The underwent extensive testing to evaluate the robustness of both hardware and software. The following features were implemented in the system.

a. Automatic shutdown in event of power failure
b. Automatic collection of initial dark values
c. Characterization of the thermal effect on lifetime

Additionally, a Data Extrapolation program was developed in house to analyze the OLED fade data. The program has the following features

a. Light Output, Temperature and Voltage parameters can be plotted for up to 20 devices.
b. Lifetime data can be extrapolated to give us T50 or T70 data.
c. The data can be filtered to remove noise due to environmental factors.

<u>Luminance, Current and Voltage (LIV) testing Station</u>

A LIV station has been designed and developed in house to test OLED products. The completely automated test system could measure both process monitor and product panels. The system is enabled to carry out angular measurements to characterize panels at different viewing angles. A Graphic User Interface (GUI, see picture below) has been developed for the system. Technical discussions with various vendors have been carried out to select critical system components.

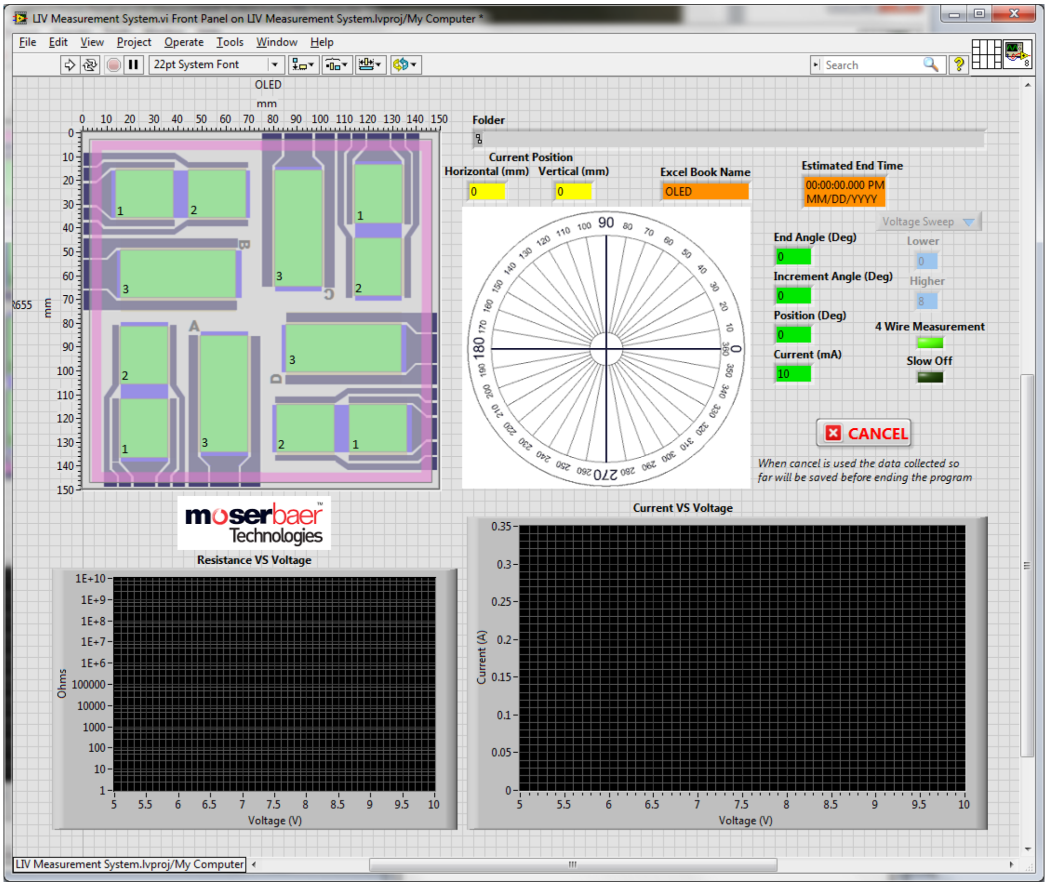


Figure 15: The Graphic User Interface for the LIV station that was developed

5. Miscellaneous and support equipment:

A complete list of required capital equipment has been compiled. This list includes wet benches, fume hoods, ovens and several pieces of analytical equipment; ellipsometer spectrophotometer, goniometer, profilometer.

F. Description of Work Performed under the Contract - extension to 2013

Task I: Project Management and Planning

We continued to develop and maintain a Project Management Plan (PMP) throughout the course of the project. We have reviewed and updated the PMP at the end of each Budget Period and resubmitted as a part of the budget period continuation application. The PMP has been modified on an ad hoc basis to reflect significant changes or deviations of planning.

Task II: Development of PHOLED Panel Technology Implementation Package

During the last year of this program we investigated methods to further improve the lifetime of a white OLED using a vertically stacked OLED (SOLED) structure consisting of two separate units. The two emissive units are connected by an internal junction. This configuration helps to extend the lifetime of white OLEDs because each unit operates at a lower current density compared with a single-unit OLED at the same luminance. Therefore, resistive power losses and Joule heating can be largely reduced, resulting in an extended lifetime especially for large area lighting panels.

We used a 2 mm^2 SOLED test pixel using a dual 2 band white structure. This dual 2 band white structure allows for outstanding color stability during aging. Device structures of dual 2 band pixel along with the standard 2 band pixel are shown in Figure 16.

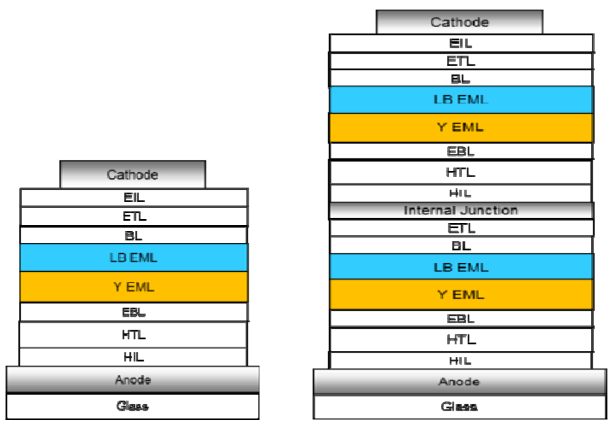


Figure 16: *Left*: Single stack device structure of pixel 1. *Right*: Two-unit stacked device structure of pixel 2.

Table 11 compares the performance data of both pixels at 1,000 cd/m^2 and 3,000 cd/m^2. For the single-unit white pixel 1, the power efficacy is 41 lm/W at 1,000 cd/m^2 and 35 lm/W at 3,000 cd/m^2. The operational lifetime is measured under various current drive acceleration conditions. An acceleration factor of 1.64 is observed. Based on the accelerated lifetime measurement, lifetime to LT70, at an initial luminance Lo=3,000 cd/m^2, is 2,100 hours. For stacked PHOLED pixel 2, the power efficacy is 40 lm/W at 1,000 cd/m^2 and 35 lm/W at 3,000 cd/m^2 without any internal or external light extraction features added. Lifetime to LT70, at an initial luminance Lo=3,000 cd/m^2, is 10,000 hours based on a measured acceleration factor of 1.69. Comparing the luminous efficacy (LE) and external quantum efficiency (EQE) of the two pixels, the stacked white

PHOLED pixel 2 achieves approximately double the luminous efficacy of the single-unit pixel 1. The two-unit stacked device achieved the same power efficacy (PE) as the single-unit architecture. Under the same driving current, the lifetime of the stacked PHOLED is measured to be ~1.4 times longer than the single unit pixel lifetime. The lifetime of pixel 2 is further enhanced because each stack can be operated at a lower current to generate the same light output as the single-unit device. Therefore the lifetime of the stacked PHOLED is enhanced by a factor of ~5 compared with a single-stack PHOLED measured from the same initial luminance. By using an index-matched external outcoupling block, >1.7x efficacy enhancement is achieved. At 3,000 cd/m^2, the stacked PHOLED pixel 2 achieved a power efficacy of 60 lm/W, which is a 12% increase compared to our last reported SOLED result with a similar YB/YB configuration. The lifetime of SOLED pixel 2 at an initial luminance of 3,000 cd/m^2 has also been improved by ~30% to LT70=25,000 hours. This is believed to be the longest lifetime reported to date of an all-phosphorescent white SOLED.

Table 11. Performance data of the single-unit (pixel 1) and stacked PHOLED (pixel 2) at 1,000 and 3,000 cd/m^2.

	Pixel 1: Single-unit OLED		**Pixel 2: Stacked OLED**			
	1,000 cd/m^2	**3,000 cd/m^2**	**1,000 cd/m^2**		**3,000 cd/m^2**	
Voltage [V]	3.7	4.2	7.3	7.1	8.2	7.8
Luminous efficacy [cd/A]	48	46	94	159	91	150
EQE [%]	23	22	42	71	41	67
Power efficacy [lm/W]	41	35	40	70	35	60
Efficacy enhancement	1.00x	1.00x	1.00x	1.76x	1.00x	1.72x
LT70 [hours]	13,000	2,100	64,000	165,000	10,000	25,000

The spectra and chromaticity data of the staked PHOLED pixel at various luminous levels are shown in Figure 3. When the driving current density varies from 1 mA/cm^2 to 10 mA/cm^2, the corresponding light output increases from 950 cd/m^2 to 8,600 cd/m^2. Compared with the spectrum at 3,000 cd/m^2, change in chromaticity on the CIE 1976 (u', v') diagram, or $\sqrt{(\Delta u^2 + \Delta v^2)}$, is within 0.014 as plotted in Figure 17. Due to this the slight shift to a warmer white color at a higher luminance i.e., the color rendering index (CRI) increases from 80 to 83 in the luminance range described.

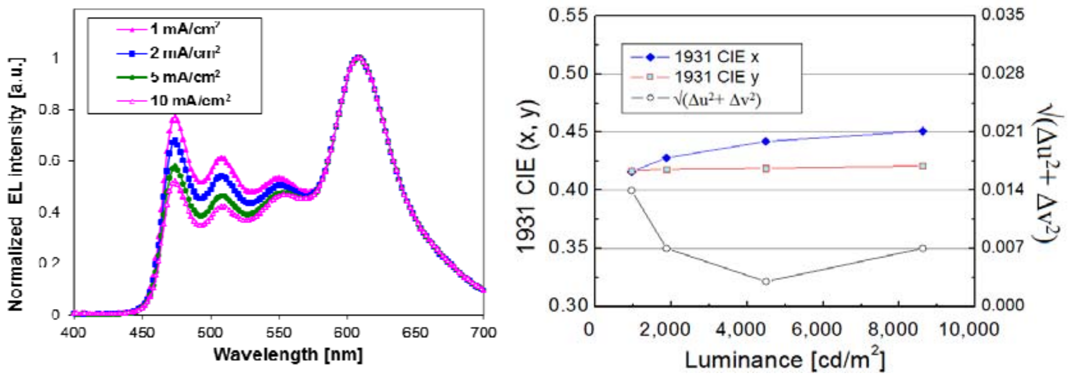


Figure 17: *Left*: White EL spectra of a stacked PHOLED pixel measured at normal incidence under various current densities. *Right*: 1931 CIE (x,y) at various luminance (left y axis) and change in chromaticity on the CIE 1976 (u', v') diagram compared to spectrum at 3,000 cd/m^2 (right y axis) of the stacked PHOLED.

Task III: Pilot Manufacturing Facility Preparation

A class 1000 clean room was built and made operational.

Task V: Production Facility Implementation – see below
Task VI: Technology Implementation – see below
Task VII: Commercial Implementation – see below

It was expected that in early 2013, equipment including, OLED deposition system, glass cleaner, encapsulation system and dehydration baking System would be installed into the cleanroom. However, due to lack of third party funding, Tasks V, VI and VII could not be completed.

G. Conclusions

In this program we successfully improved OLED technology to demonstrate performances of lighting panels that could meet early entry commercial requirements. We designed and had assembled a custom OLED deposition tool that could be used to manufacture OLED lighting panels through a novel low cost manufacturing strategy, based on the high throughput processing of small area substrates. A custom clean room was built in NY State in preparation for the first U.S. based OLED pilot line. In addition we developed a cost model to allow us to develop cost roadmaps and show strategies for achieving DOE cost targets. While we were unable to complete the OLED lighting pilot line and provide samples to luminaire companies, our efforts improved OLED lighting technologies and identified strategies to accomplish the low cost U.S. based manufacture of OLED lighting to enable the production of early entry products.