Solid State Lighting Program
Final report

September 30, 2010

DEVELOPMENT of HIGH EFFICACY, LOW COST PHOSPHORESCENT OLED LIGHTING LUMINAIRE

Work Performed Under Agreement:
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Period of Performance

July 7 2008 – July 6, 2010

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A. Project summary

In this two year program, UDC together with Armstrong World Industries, Professor Stephen Forrest (University of Michigan) and Professor Mark Thompson (University of Southern California) planned to develop and deliver high efficiency OLED lighting luminaires as part of an integrated ceiling illumination system that exceed the Department of Energy (DOE) 2010 performance projections. Specifically the UDC team in 2010 delivered two prototype OLED ceiling illumination systems, each consisting of four individual OLED lighting panels on glass integrated into Armstrong's novel TechZone open architecture ceiling systems, at an overall system efficacy of 51 lm/W , a CRI = 85 and a projected lifetime to 70% of initial luminance to exceed 10,000 hours. This accomplishment represents a 50% increase in luminaire efficacy and a factor of two in lifetime over that outlined in the solicitation. In addition, the team has also delivered one 15cm x 15cm lighting panel fabricated on a flexible metal foil substrate, demonstrating the possibility using OLEDs in a range of form factors.

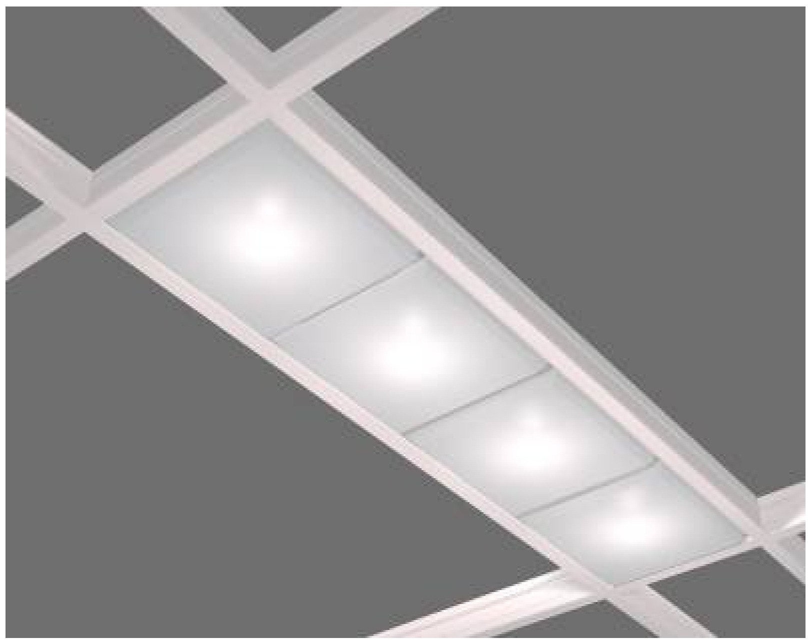

Figure 1: This is a rendering of how the luminaire will appear in the ceiling grid.

During this program, our Team has pursued the commercialization of these OLED based ceiling luminaires, with a goal to launch commercial products within the next three years. We have proven that our team is ideally suited to develop these highly novel and efficient solid state lighting luminaires, having both the technical experience and commercial strategy to leverage work performed under this contract. Our calculations show that the success of our program could lead to energy savings of more than 0.5 quads or 8 MMTC (million metric tons of carbon) per year by 2016.

B. Accomplishments

All Milestones were completed on time.

- **Demonstrated a white PHOLED pixel with a luminous efficiency of 68 lm/W at 1000 cd/m^2 with a CRI of 80 and a color coordinate of (0.42, 0.42).**

- **Demonstrated a 15cm x 15cm white OLED lighting panel with a luminous efficiency of 42.6 lm/W at 1000 cd/m^2 and a color coordinate of (0.392, 0.42).**

- **Delivered a 15cm x 15cm white OLED lighting panel on a flexible metal foil substrate**

- **Delivered 2 OLED lighting luminairies**
  - **Each luminairie contained four 15cm x 15cm OLED lighting panel**
  - **The OLED panel efficacy was 58 lm/W at 1000 cd/m^2**
  - **Luminaires operated at 24 volts**

- **Completed OLED Lighting Commercialization Roadmap**

C. Milestone Summary

Year 1	**Milestone**	**Schedule**
Milestone 1	Design document outlining details of OLED lighting luminaire, including OLED panel and electronics design.	Reported on time, June 30, 2009
Milestone 2	OLED 2 mm^2 pixel demonstrating 60 lm/W at 1,000 cd/m^2	Reported on time, December 31, 2008
Milestone 3	OLED 15cm x 15cm lighting panel demonstrating 35 lm/W at 1,000 cd/m^2	Reported on time, June 30, 2009
Year 2		
Milestone 4	Demonstrate 15cm x 15cm lighting panel prototype on flexible metal foil substrate	Delivered on time, December 31, 2009
Milestone 5	Deliver 2 OLED lighting luminaires that exceed 300 lumens, > 55 lm/W efficacy, with panel LT70 > 10,000 hours with CRI > 85.	Completed on time, June 30, 2010
Milestone 6	Deliver a commercialization roadmap outlining path to launch of OLED lighting products.	Reported on time, June 30, 2010

D. Background

System Analysis

The goal of this project was to show that our team has the unique ability to deliver an OLED luminaire that exceeds the performance specifications outlined in the DOE Funding Opportunity Announcement. Specifically we planned to deliver a prototype luminaire having the performance outlined in Table 1, and integrate this luminaire into Armstrong's TechZone ceiling systems.

METRIC	Solicitation requirement	UDC Team Goal for 2010 PHOLED luminaire
Efficacy – Commercial (lm/W)	35	55
CRI	80	85
Luminous flux (lumens)	300	>300
Lamp lifetime (LT70) (hrs)	5,000	10,000

Table 1: Comparison of UDC planned versus DOE required luminaire performance.

Our luminaire deliverable was designed to meet or exceed all the performance requirements outlined in the solicitation. Our panel will have a CRI = 85, at LT70 = 10,000 hours (double the solicitation target). The overall luminaire consists of three key components (Figure 2): drive electronics, OLED lighting panel, and mechanical fixture, each of which has its own efficiency and cost.

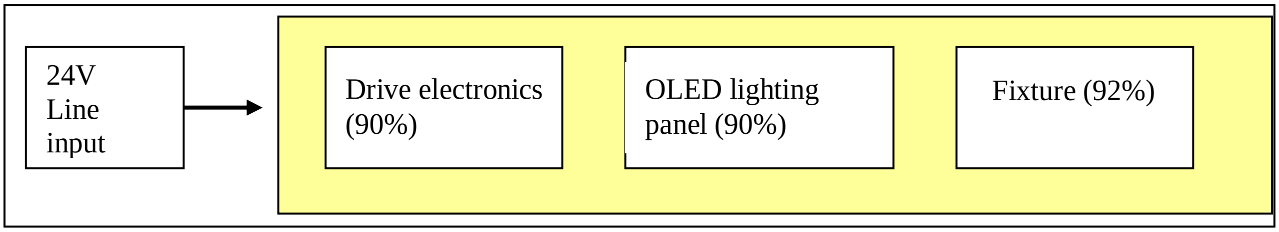

Figure 2: Key components of OLED luminaire with their associated electrical efficiencies. The panel efficiency is 90% of an individual pixel performance (75 lm/W).

The overall luminaire is designed to consist of 4 individual lighting panels within the luminaire fixture (ceiling system), operating from a 24V line input. We have selected this input as it now appears set to become the industry standard for ceiling lighting. For convenience, the luminaire deliverables to the DOE will also include an additional external power supply for 110V line inputs.

Previous Work and Technical Strategy

UDC is a world leader in the field of organic light emitting materials, device, and process research and development. UDC has a team of 40 scientists and engineers focusing in these areas, and longstanding exclusive collaborations with Professor Stephen Forrest and his research team at the University of Michigan; and, Professor Mark Thompson and his team at the University of Southern California (USC) both pioneers in PHOLED research. Today, UDC and our research partners are recognized as pioneers in the area of organic electronics research, and their development for commercial applications. For the past eight years, the team has focused exclusively on developing state-of-the-art PHOLED technology.

Our team's invention, followed by continuing development of phosphorescent OLEDs is a key technology that will enable OLEDs to become an efficient and viable general illumination light source. Today UDC's PHOLED technology is acknowledged as a critical element to the success of OLEDs for both flat panel display and lighting applications. Furthermore, the compatibility of OLEDs for use on flexible substrates pioneered by our team opens up the possibility for a new generation of illumination sources that are conformable, rugged and extremely light weight. In addition, the ability to produce these PHOLEDs on plastic or metal substrates enables the use of roll-to-roll manufacturing techniques to significantly reduce manufacturing costs. Hence, there are many compelling arguments for pursuing phosphorescent OLEDs for the next generation of low cost solid-state light sources.

Over the last 5 years, UDC has demonstrated consistent improvements in the power efficacy of white PHOLEDs from 5 lm/W to 102 lm/W. In 2008, UDC successfully demonstrated an all phosphorescent white organic light emitting diode (WOLED^{TM}) with a power efficacy of 102 lm/W at 1,000 cd/m^2. These high efficacy values are comparable to fluorescent lamps, especially when the fluorescent luminaire efficiency is taken into consideration. Table II lists the 102 lm/W device characteristics and compares them to targets to achieve a 150 lm/W Energy Star device by 2015, and the goals of this effort. Our high-efficacy device was enabled by lowering the device operating voltage, increasing the outcoupling efficiency to 40% from 20%, and by incorporating highly efficient phosphorescent emitters that are capable of converting nearly all current passing through a WOLED into light. Warm white emission from the device has a color rendering index of 70 at (0.41, 0.46), and this color was chosen because it more closely resembles the color of Illuminant A standard incandescent, which WOLEDs may replace in the lighting industry.

This program had a target efficacy of 75 lm/W with a CRI of 85 for individual PHOLED pixels by 2010 to enable an overall luminaire efficacy of 55 lm/W, including losses from drive electronics, and this goal will be achieved by addressing three key efficiency parameters. For a Lambertian emission OLED source, where V = operating voltage and η_{lum} is luminance efficiency (cd/A) (A=Amps), the power efficacy (η) is given by $\eta = \eta_{lum} \cdot \pi / V$, and $\eta_{lum} = k \cdot \eta_{int}\ \eta_{out}$, where η_{int} = internal quantum efficiency

(% excitons to photons), and η_{out} = outcoupling efficiency (% of photons emitted into air to generated photons), and k is a constant dependent on the photopic response of the human eye; hence,

$$\eta = \frac{k \cdot n_{lum} \cdot n_{out} \cdot \pi}{V} \qquad (1)$$

As a result, power efficiency is a function of internal quantum efficiency, $\boldsymbol{\eta_{int}}$**,** light extraction, $\boldsymbol{\eta_{out}}$, and voltage, **V.** Thus, to improve device performance, advances in these areas are required. To realize a 75 lm/W pixel, our plan is to achieve the following individual performance metrics: (a) 90% internal quantum efficiency, (b) <3.8 V operating voltage at a target luminance of 1,000 cd/m^2, and (c) 40% outcoupling efficiency.

E. Phase 1 (Months 1 -12) Luminaire Design

Design Strategy

During the design phase of this project, several design meetings were held which included all the team members; UDC, Armstrong and Technokon. Key features that resulted from these meeting and have been included in the design are as follows:

1. The outcoupling lens is designed to sit on a lip of the fixture to allow for easy removal of each lamp from the overall luminaire.
2. Contact pads for the lamp power are all on one side to simplify electronics connection to the lamps.
3. The 4 lamps will be connected together in series to simply the electronics, and reduce the number of electrical connections.
4. Electrical connection to the lamps will be by pressure connections using a conductive elastomer. This will simplify lamp replacement.

Once the initial design was completed and the first luminaires were assembled, it was found that changes to the original design were required to meet the program milestones. These changes included:

1. The lighting panel needed to be located below the ceiling to allow the light trapped inside the glass substrate to be emitted below the ceiling. This required a redesign of the lens and fixture
2. The lighting panel was found to have poor uniformity, a large power loss due to the resistance of the ITO and a poor. A new panel layout was designed with lower IR losses which provided much better performance.

Task 1: OLED Panel Design for High Efficiency

Panel Design

The OLED panel's active area has been segmented into 10 large pixels, see Figure 3. Each pixel will be surrounded by a 1mm wide low resistance gold bus line. The size of the bus line was increased by 10x over previous designs after determining the maximum voltage drop across a bus line with the fixture operating at maximum luminance. Assumptions and calculations are given in Table 3.

A 10 pixel pattern was selected with an IR drop of 0.61 volts, resulting in an electrical loss of approximately 17% when based on an operating voltage of 3.5V. Although fewer, larger pixels would result in a smaller electrical loss, the yield from the larger pixels would be much lower. The calculations for the IR drops are summarized in Table 3.

With 0.1mm Buss Bar

Individual Pixel Dimension (cm)		Individual Pixel Area					
Length	**width**	**cm^2**	**mA/pixel**	**sq/ pixel**	**ohm/ pixel**	**# pixels/ plate**	**plate voltage**
6.39	0.6	3.834	19.17	10.65	31.95	40	24.50
6.39	1.2	7.668	38.34	5.32	15.98	20	12.25
6.39	2.4	15.33	76.68	2.66	7.98	10	6.12
6.39	3	19.17	95.85	2.13	6.39	8	4.90
6.39	6	38.34	191.7	1.06	3.19	4	2.45

With 1mm Buss Bar

Individual Pixel Dimension (cm)		Individual Pixel Area					
Length	**width**	**cm^2**	**mA/pixel**	**sq/ pixel**	**ohm/ pixel**	**# pixels/ plate**	**plate voltage**
6.39	0.6	3.834	19.17	10.65	3.195	40	2.45
6.39	1.2	7.668	38.34	5.32	1.59	20	1.22
6.39	2.4	15.33	76.68	2.66	0.798	10	0.61
6.39	3	19.17	95.85	2.13	0.639	8	0.49
6.39	6	38.34	191.7	1.06	0.319	4	0.24

Assumptions

Current required for 2000 nits is $5mA/cm^2$ (40cd/A)
0.1mm Buss bar to provide 3X improvement in resistivity
Using low resistance ITO coated substrate 4.5Ω/sq

Table 2: Calculations used to determine the size of the pixels and the number of pixels to be used in the layout of the lighting panel. The panel design parameters selected are highlighted.

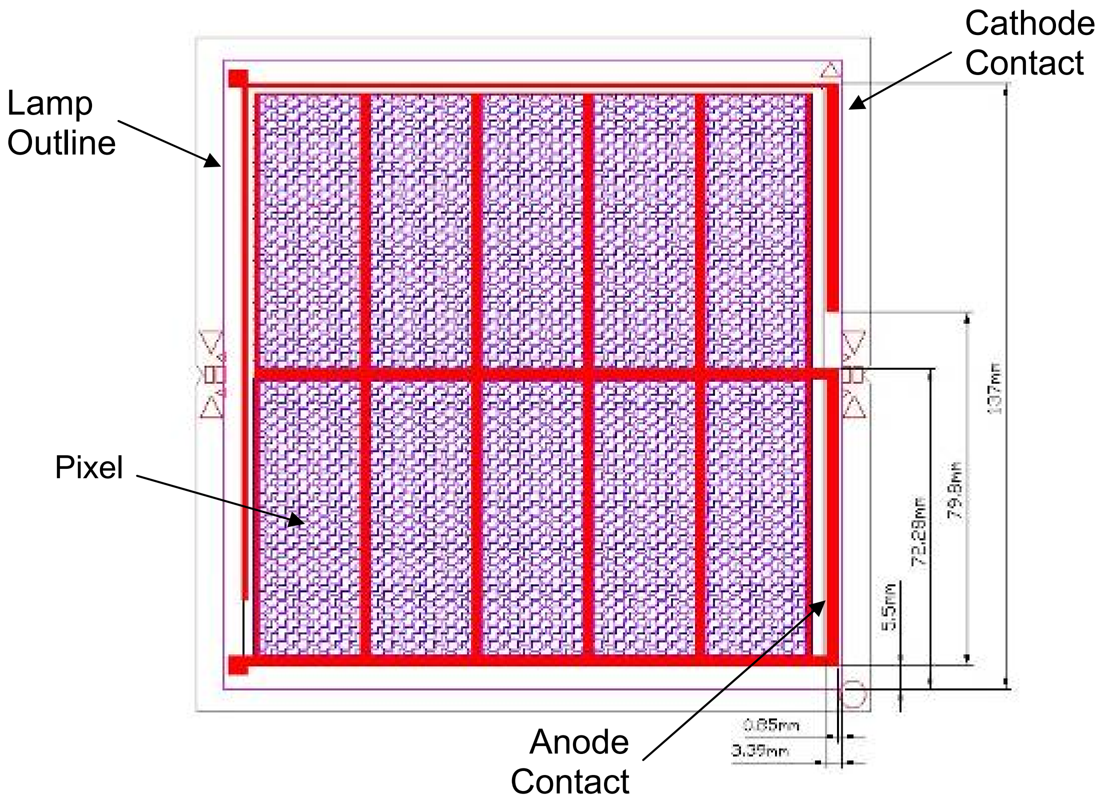

Figure 3: Design of the light panel. There are 10 pixels that are surrounded by 1mm gold buss lines that are show in red.

When the display was designed, there was trade off between thick bus lines that would result in improved uniformity, but with a higher probability of shorting, versus thinner bus lines, with reduced uniformity, but fewer shorts. The thicker bus lines are more likely to create shorts due to potential step coverage issues associated with insufficient coverage of the insulating grid material over the bus line and/or bus line edge spikes that can be caused by the lift-off process used to form the bus lines. The thinner bus lines were selected for the first panel fabrication due to the reduced possibility of shorting. Once the substrates were made and OLEDs were fabricated, it was found that the uniformity of the panel was not acceptable. As expected, once the thickness of the buss lines which surrounded each pixel was increased by a factor of 4, the uniformity improved, but the yield decreased due to shorting (see Figure 4).

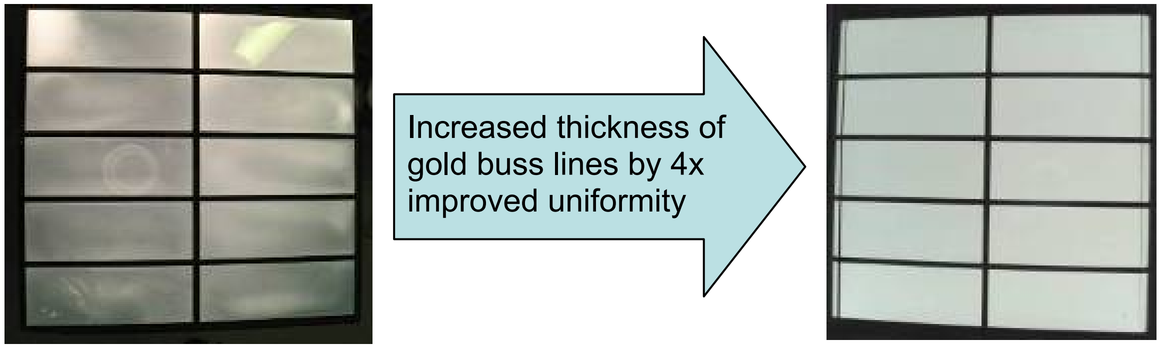

Figure 4: The pictures show the uniformity improvement achieved by increasing the thickness of the gold buss lines by 4X.

To improve both yield and uniformity, a new panel layout was designed using 4 large pixels on a substrate that are connected by a series circuit design. The series circuit design allows the pixels to be operational if a short occurs. If a short occurred on the previous design, the entire panel would be unable to be turned on. Each large pixel has several small buss lines in it which improves the uniformity. Since the distance between the buss lines is small, the buss line thickness can be reduced, thus reducing the process time required for making the substrate. This is an additional advantage over the previous design. The small buss lines are not distinguishable when viewed from approximately 1m away. See Figure 5 for the panel design.

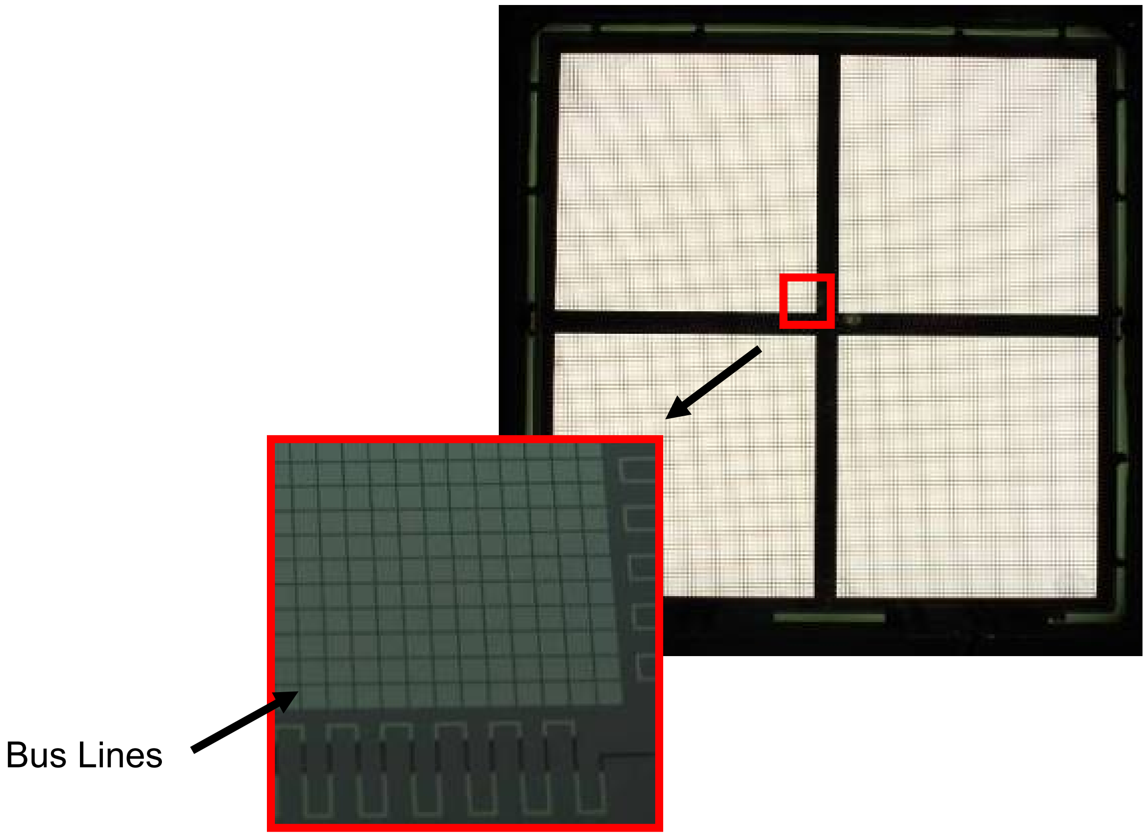

Figure 5: Picture of the final panel layout. The four large pixels are in a series circuit. There are small buss lines through out each pixel to improve the uniformity which are shown in the inset.

Lens Design

The lens as designed will be made out of clear acrylic. For the initial design, the top of the lens has a cavity in which the lighting panel is placed. The outside edges of the cavity are angled at 30° to reflect the light out the front of the lens that is coming out the edges of the glass. Along 2 edges of the lens there are ledges for where the lens will sit on the fixture. See Figure 6 for the initial lens drawing.

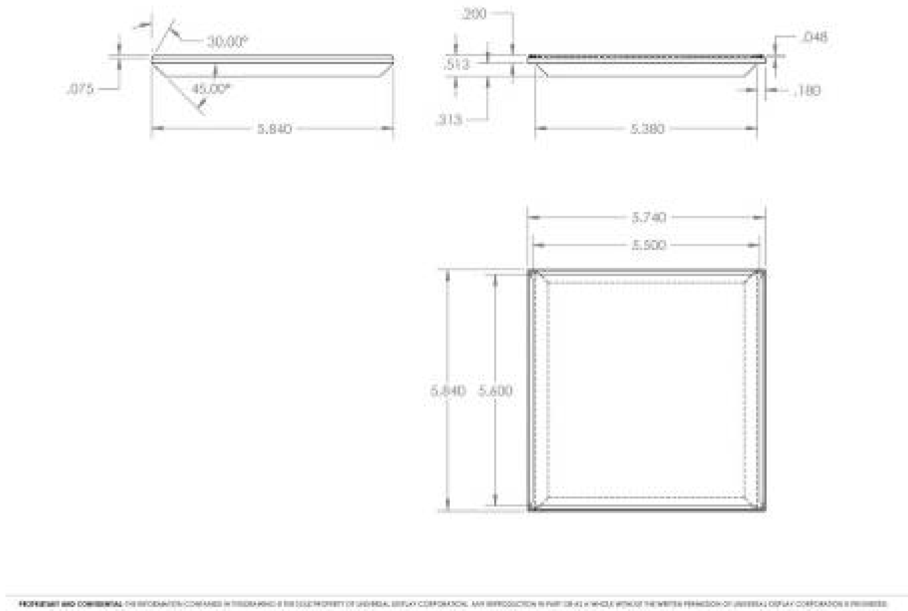

Figure 6: The drawing of the lens for fixture design 1.

A second lens was design to be used to be mounted under the ceiling. Similarly to the first lens, the top of the lens has a cavity in which the lighting panel is placed. The bottom surface of the lens has a curved design to optimize the light output. This design will also be made out of clear acrylic. See Figure 7 for the final lens design.

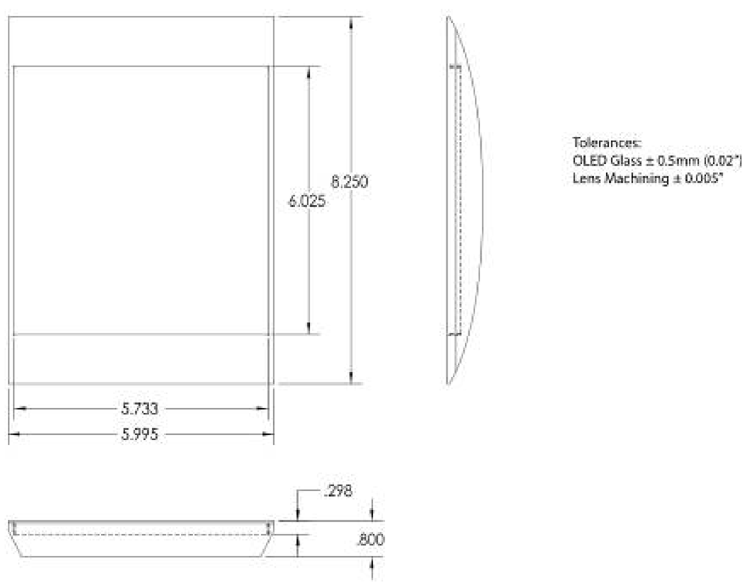

Figure 7: This is the drawing of the lens that is used for the final deliverable.

Task 2.0 Efficient Power Supply and Electrical Design

The OLED luminaire driver circuit provides a constant current to the OLED lamps of the luminaire from a 24 VDC power supply. It comprises a highly efficient switch mode buck regulator configured as a current source. There are four OLED lamps connected in series. See Figure 8 for a schematic of the luminaire drive circuit.

Lamps Interface

1. The driver board provides the lamps a controlled current between approximately 0 to 1.0 amps DC as set by the 0-10 volt brightness input provided at the input.
2. The lamps provide a load voltage at full current of less than 22 volts.
3. The driver board provides the controlled current via a Molex 70533-0036 connector. Pin 1 is negative.

External Interface

1. The driver board accepts a 24 volt DC power supply input.
2. The driver board accepts a 0-10 volt brightness input. This input is a “pull-down” input, i.e., if unconnected, the driver outputs the maximum current. To reduce the current the brightness input must be “pulled down” to a lower voltage. The current is proportional to the voltage on the brightness input.
3. The external interface is provided via a Molex 70543-0037 connector. Pin 1 is the negative input from the power supply. Pin 3 is the positive input from the power supply. Pin 2 is the brightness input.

Dimensions and mounting

The driver board is 2.0” by 2.0” and has four 0.125” diameter holes in the corners, spaced 0.25” away from the board edges, for mounting. Figure 9 shows the details of the mechanical mounting.

Brief Technical Description

Q1 is the switch element of the power supply. Its operation is controlled by U3 (a current measurement circuit), U1 (a comparator), and U2 (a digital latch) in conjunction with a clock signal provided by U4. If the measured current exceeds the reference signal (provided from an external control signal in conjunction with R1, R2, R3 and C3), the switch is turned OFF at the rising edge of the clock signal. Otherwise, it is turned OFF.

R5 provides the minimum current required to operate the circuit at start-up. This current is insufficient to provide the power required for normal operation however. The power required for normal operation is derived from the fly-back pulses from the drain of Q1 via C5 and D1. The value of C5 is set such that the energy required to drive the gate of Q1 is just provided via C5 during the fly-back pulse. This, together with the switch mode topology of the circuit minimizes the overall losses associated with circuit operation.

U4 is a microcomputer that both provides the clock that is used for operation of the circuit and provides an extra degree of circuit supervision. It also monitors the current level sensed by U3 and, if the current exceeds 1.25A, it shuts the switch off, thereby preventing a run-away current condition. The circuit is also fuse protected by means of resettable fuse F1.

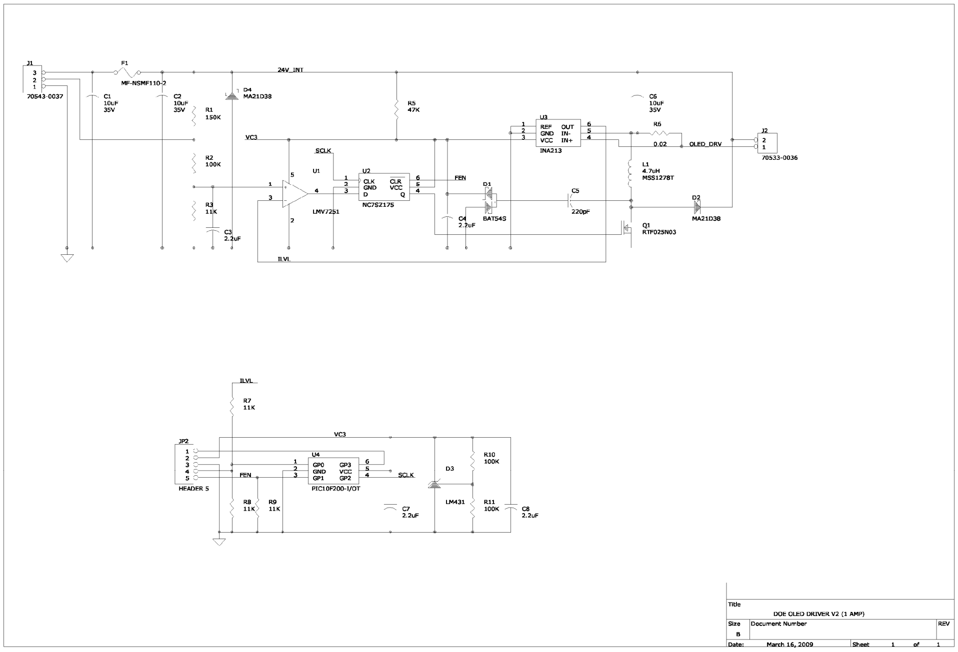

Figure 8: Schematic of the luminaire drive circuit

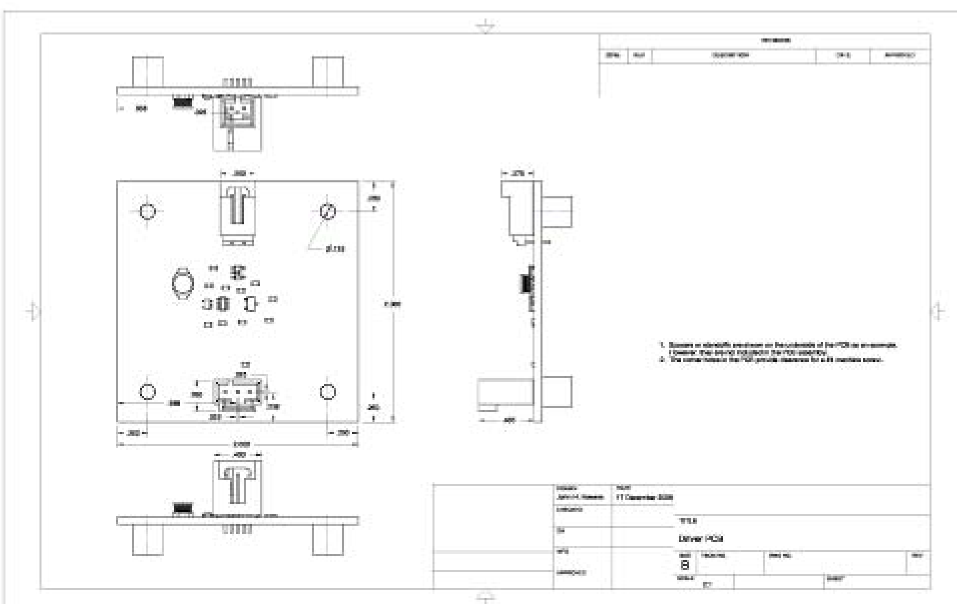

Figure 9: Drawing of the electronics board

Task 3.0 Mechanical Fixturing and Ceiling Panel Design

Intended Use

The fixture is designed to mount, secure and provide power and control interfaces for 4 OLED lamp assemblies and their driver electronics. It is intended for installation in Armstrong's TechZone® suspended ceiling system.

Construction

There were 2 fixture designs completed for this project. Once Design 1 was fabricated, it was found that design changes were required to meet the milestones. A second fixture design was completed and fabricated for the deliverable. The key difference between the 2 designs was that Design 1 had the lighting panel mounted above the ceiling while Design 2 had the lighting panel mounted below the ceiling.

For both of the designs, the components are constructed of 23-gage (minimum), cold rolled steel and is coated with a corrosion resistant paint. Both fixtures accept 4 lamp assemblies.

Design 1: The fixture was comprised of 3 major components, lamp mounting frame, back plate and electronic enclosure. The lamps are held in place by an interference fit on their face side and a compression fit on their back side. The back plate provides this compression fit by hinging on the lamp frame on one side and snapping into the lamp frame on the other. The back plate also provides a mounting surface for the electronics, power connector and electronics enclosure. The electronic enclosure has tabs that snap into slots in the back plate. Power for the OLED lamps is provided from the driver electronics via a wiring harness comprised of 16 AWG wire and a conductive elastomeric extrusion. The contact to and from each individual lamp is made through the conductive elastomeric extrusion through a compression fit. See Figure 10.

Design 2: The fixture was also comprised of 3 major components the back pan, lamp mounting frame and the electronics enclosure. The lamp mounting frame is connected to each lens by set screws on each end. There are 4 hooks on the lamp mounting frame that fit through small holes in the back pan to hang the lamp under the ceiling. Electrical connection to the lamp is made through wires soldered to the electrodes on the lamp and connectors attached to the other end of the leads to plug into connectors mounted to the back pan. The back pan also provides a mounting surface for the electronics, lamp connector, power connector and electronics enclosure. See Figures 11 through 13.

Dimensions / Weight

Maximum overall dimensions for both fixtures are (L x W x H) 23.79" x 5.86" x 2.09"
Estimated weight is 5 lbs.

Mounting

Both fixtures are sized to rest on the T-bar flange that supports the ceiling panels. Integral T-bar clips will positively secure fixture to T-bar.

Power Interfaces

Input power for the luminaire electronics and lamps is provided through a connector making connection to the 24 VDC power for the bus system.

Dimming Control Interface

A terminal block accepting # 12-24 AWG wire, mounted at the electronic enclosure will accept the control input.

Lamp Maintenance

Design 1: The fixture opens to allow access to each individual OLED lamp, allowing replacement from above the ceiling.

Design 2: The lamps are suspended from the ceiling using hooks to secure the lamp to the back pan. The lamps can be replaced from below the ceiling by unhooking them from the back pan.

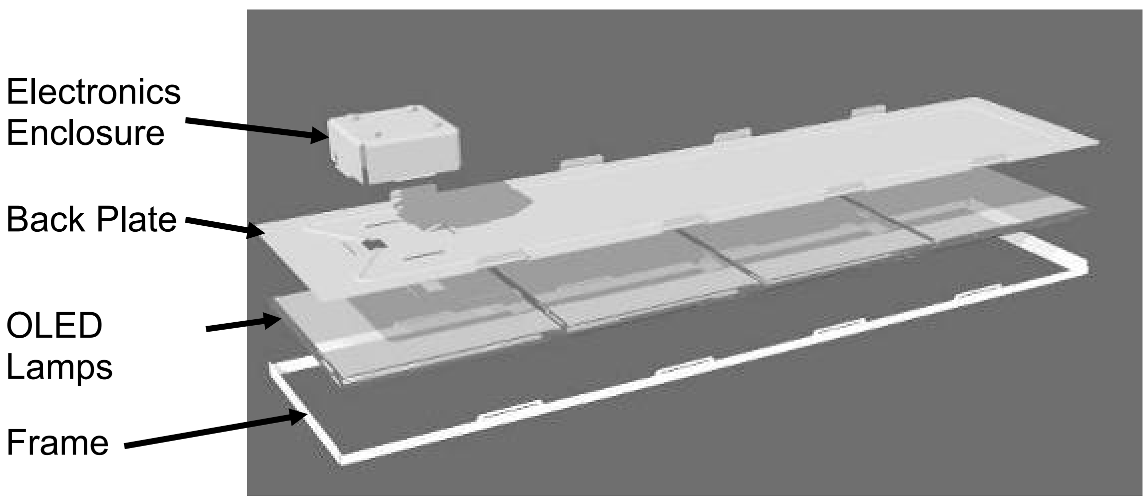

Figure 10: Rendering of the first fixture design in which the lenses were mounted above the ceiling.

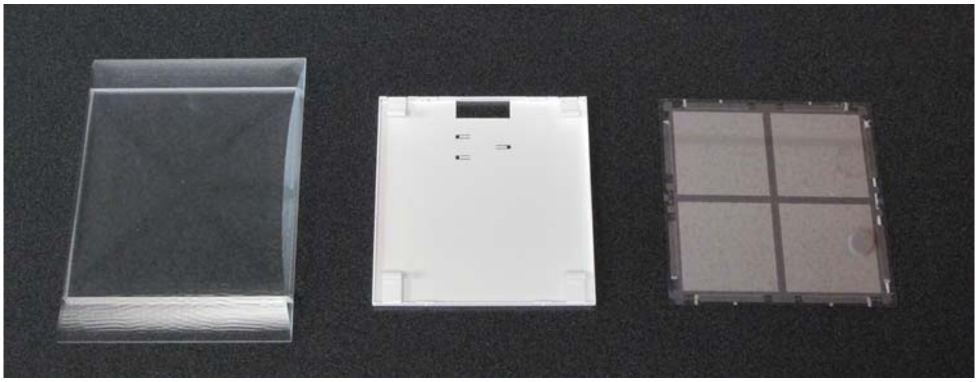

Figure 11: The three components that make up the OLED lamp; from left to right, lens, lamp mounting frame and the OLED light plate.

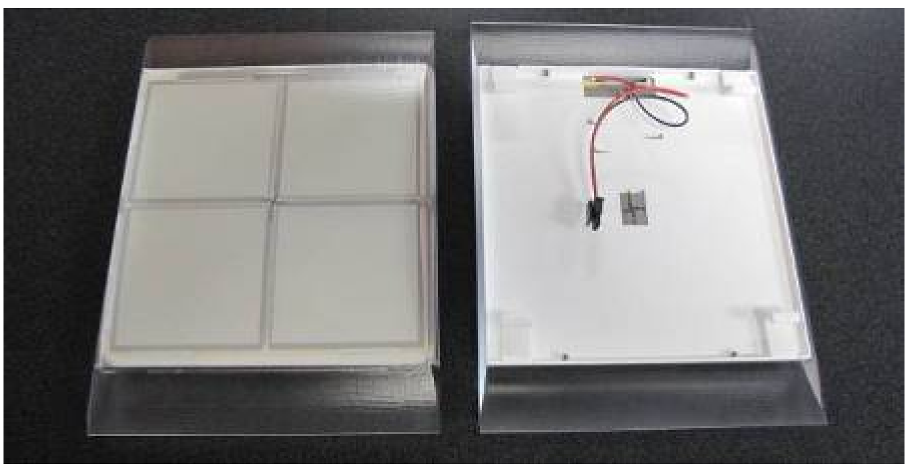

Figure 12: Assembled OLED lamps

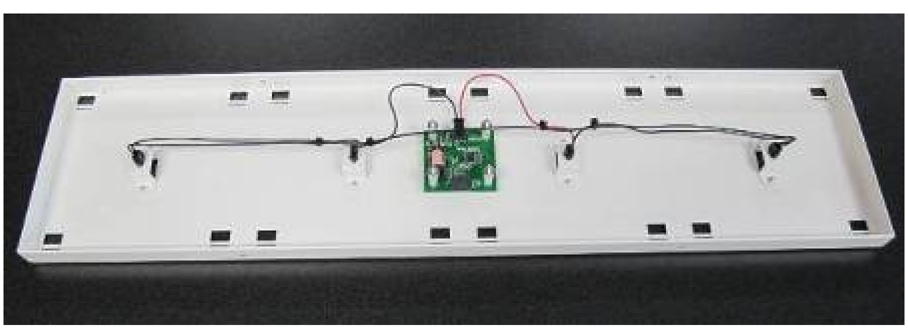

Figure 13: This picture show the back pan with the electronics attached and wiring for the OLED lamps installed.

Task 4.0 OLED Device Architecture

In January 2009 we reported that we had fabricated a white OLED device that has met Milestone 1: OLED 2 mm^2 pixel demonstrating >60 lm/W at 1,000 cd/m^2. The device was measured in an integrating sphere using an outcoupling lens and achieved a luminous efficiency of 68 lm/W. The performance data for the pixel is shown in Table 3.

	No Outcoupling	With Outcoupling
Luminous Efficiency	33 lm/W	68 lm/W
CRI	80	80
Luminance	1,000 cd/m^2	1,000 cd/m^2
EQE	19.6 %	40.4 %
Voltage	4.0 V	3.8 V
Color Coordinate	(0.42, 0.42)	(0.42, 0.42)
Color Temperature	3420 K	3420 K
Lifetime (LT50) at 1000 nits	> 17,000 hrs	> 47,000 hrs

Table 3: *Milestone 1* - Results from 2 mm^2 OLED pixel demonstrating 60 lm/W at 1,000 cd/m^2.

The OLED structure to be used for the program lighting panel is based on the results above, and incorporated UDC's high efficiency organic structure, as shown in Figure 14. Several test devices have been made using the high efficiency WOLED structure varying both film thickness and host/dopant ratios. We have found that there often is a trade-off between CRI, lifetime and efficiency.

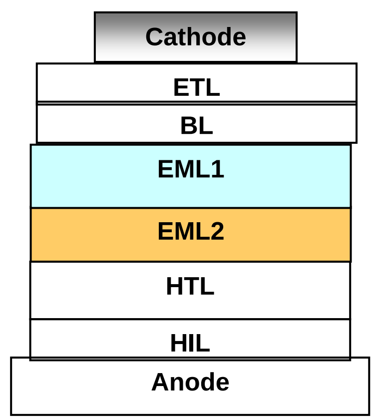

Figure 14: The structure for the high efficiency WOLEDs.

In June 2009 we reported the completion of Milestone 3, fabricating a white 15cm x 15cm OLED device that has exceeded the 35 lm/W at 1,000 cd/m^2 requirement.

The performance of the OLED lighting panel was 42.6 lm/W at 1000 cd/m^2 measured in an integrating sphere using an outcoupling block with index matching fluid. The device voltage was 3.97 V with a current density of 1.86 mA/cm^2. There was no voltage loss when transferring the structure from 2mm^2 device, where the device structure was developed and tested, to the large area lighting panel. The CIE coordinates are (0.390, 0.417).

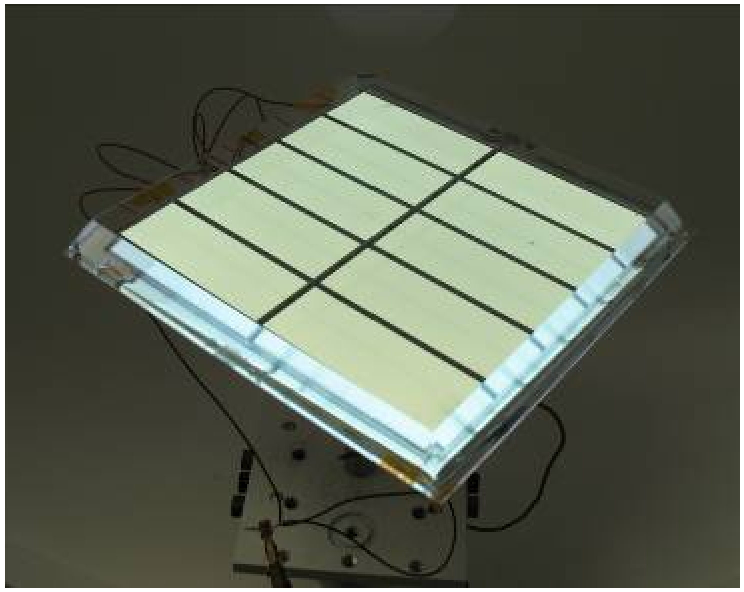

Figure 15: 15cm x 15cm lighting panel with a performance of 42.6 lm/W at 1000 nits measured in an integrating sphere using an outcoupling block with index matching fluid

F. Phase 2 (Months 1 – 24) Focused Short Term Applied Research

Task 5.0 – Development of novel low cost microlens arrays

The University of Michigan (UM) worked on extracting the light that is trapped within the OLED device. In a conventional OLED over 50% of the emitted light is trapped in the high-index organic and ITO layers reducing the efficiency of the device. See Figure 16. In order to extract this waveguided light, a grid composed of a low-index dielectric (LIG) is embedded into the organic layers. The LIG extracts light into the substrate where it can be further outcoupled to the forward viewing direction by other methods e.g. microlens arrays. Simulations have shown that reducing the refractive index of the grid increases light extraction.

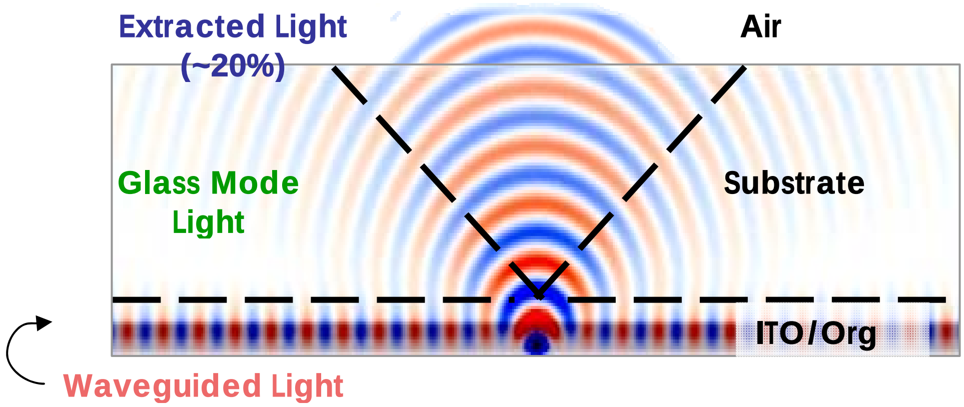

Figure 16: This graphic shows how the emitted light is trapped in the high-index organic and ITO layers reducing the efficiency of the device.

By obliquely depositing material, a highly porous film can be created due to self-shadowing. The increased porosity, reduces the effective refractive index: n = 1.05 films have been demonstrated using this method. The features are much smaller than the wavelength of emitted light making the film optically continuous. The porous film is also structurally rigid allowing patterning of a grid by standard lithographic methods.

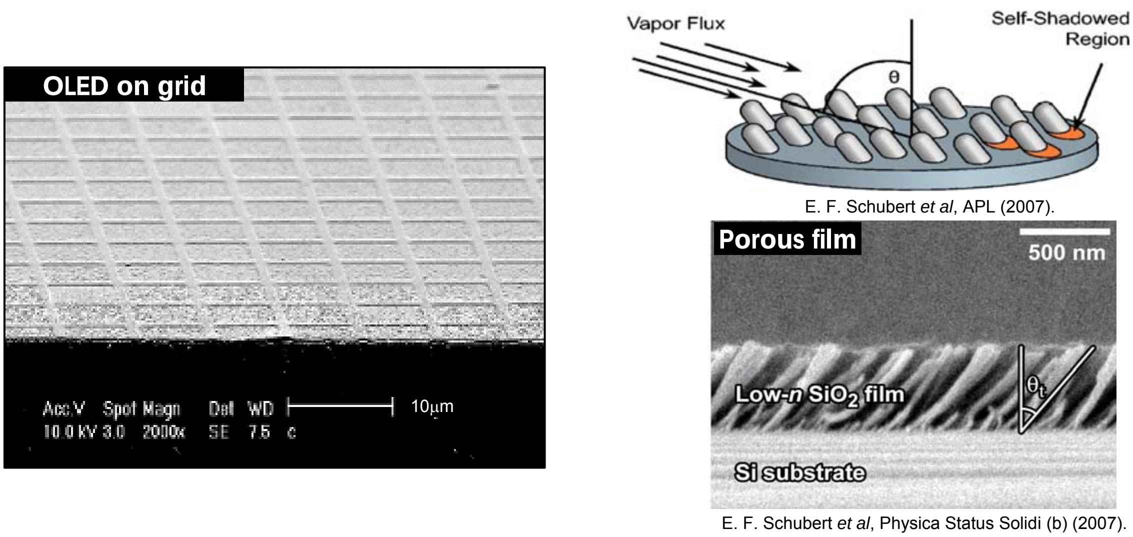

Figure 17: The SEM micrograph on the left is the porous film patterned into a grid. OLED materials have been deposited on the grid in the picture. The graphic on the right shows how the porous material is deposited creating the self-shadowed region. The micrograph below shows an example of the porous film that was grown on a Si substrate.

UM has been experimenting with the LIG material. See Figure 18. The UltraLIG shows better enhancement of external quantum efficiency (EQE) as well as power efficiency. The enhancement is more pronounced when glass mode light is included (as expected) necessitating a further substrate outcoupling method

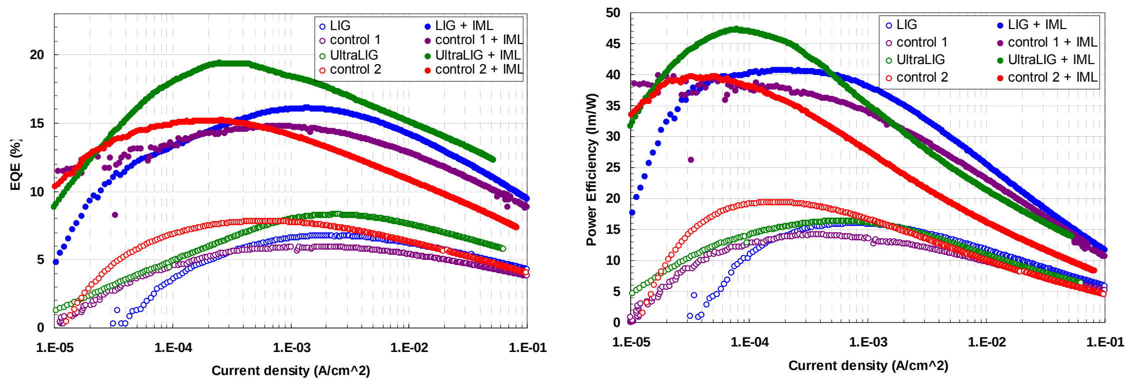

Figure 18: The low-index grid (LIG) is composed of SiO2 with n=1.45. The ultra-low-index grid (UltraLIG) is made from obliquely deposited porous SiO2 with n=1.16. LIG devices were grown at the same time as Control 1, while UltraLIG devices were grown with Control 2. Index Matching Liquid (IML) was applied between the substrate and the photodetector to measure glass modes.

G. Phase 3 (Months 13 -18) Demonstration of Flexible Form Factor

Task 7.0 Metal Foil Planarization & Task 8.0 Flexible Fabrication

In December of 2009, we completed Milestone 4, the demonstration and delivery of a 15cm x 15cm OLED lighting panel fabricated on a flexible metal foil backplane. The metal foil substrate was 0.10mm planarized stainless steel. The pattern of the flexible lighting panel had 4 large squares made up of 6 rectangular pixels that are 50mm long by 7 mm wide. The pattern utilizes buss bars around each pixel to improve the uniformity of each pixel. Evaporated metal was used to connect the pixels together to reduce the number of electrical connections. The display was thin film encapsulated and then a protective AR hardcoat film was laminated to the substrate. Since the metal foil is opaque, the device architecture for the WOLED was changed and optimized for a top emission device.

The lighting panel was driven by a power supply box delivered with the display with 4 electrical connections the panel. See Figure 19.

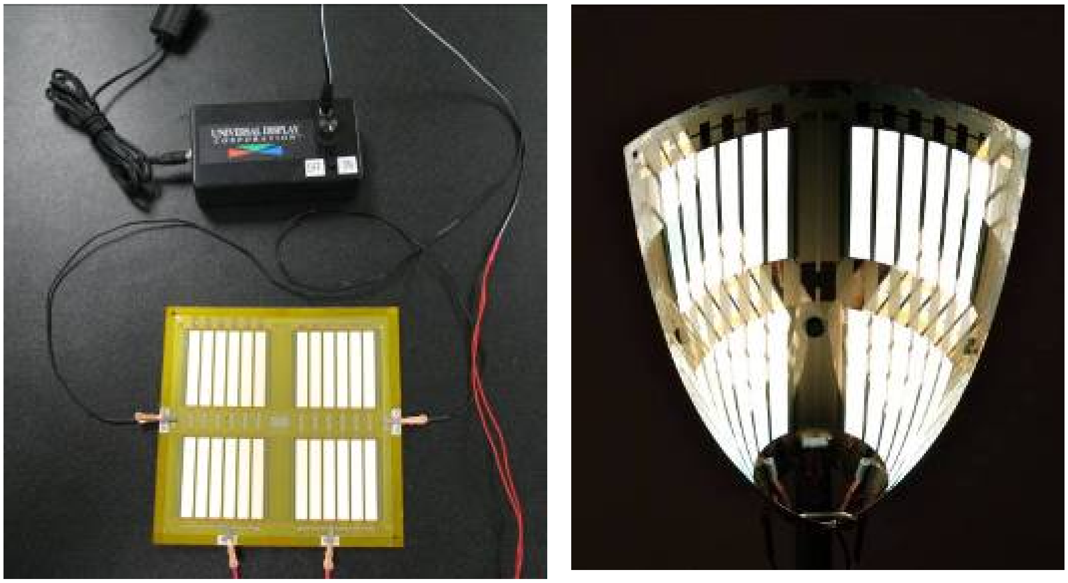

Figure 19: The 15cm x 15cm OLED lighting panel fabricated on a flexible metal foil backplane in operation. Shown are the materials that were supplied as part of the flexible lighting panel kit, which included: electrical control box; power supply for control box; interconnect wires; flexible light panel.

H. Phase 4 (Months 19 -24) Luminaire Fabrication

Task 9.0 OLED Panel Fabrication

During this final period of the project, further progress was made on improving the reliability of the lighting panels. The OLED growths have been optimized for performance and repeatability by making subtle adjustments to the device architecture. These changes have resulted in a large area lighting panel having an efficacy of 50 lm/W and a CRI of 87 at 1000 cd/m^2. This achievement was the result of the development of a new light blue phosphorescent emitter developed outside of this program. The new blue emitter has also allowed us to simplify the OLED structure to six layers in the organic stack. See Figure 20.

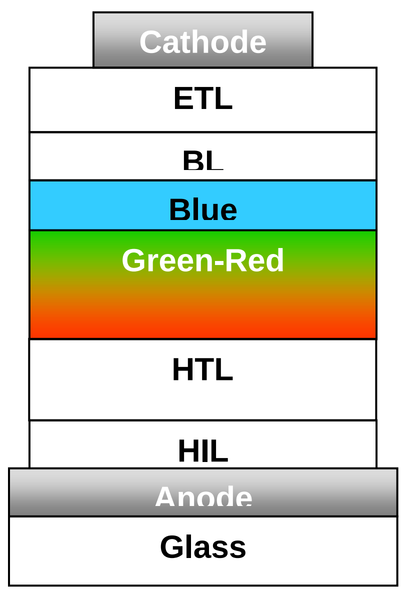

Figure 20: 6 layer organic structure that will be used for the white lighting panels.

For the final deliverable, a new OLED driver was designed and constructed for the series connected OLED pixels that now result in 18 volts per panel and 72 volts per series string (of 4 panels) at about 100mA. The driver is a flyback converter operating in discontinuous mode, but nearly critical conduction mode -- generally the highest efficiency configuration. It's primary components are a PIC18F1826 microcomputer for developing drive signal and monitoring the feedback signals (output voltage and current) and the current reference signal; a gallium nitride FET that provides an exceptional combination of low Rds(on), high drain voltage capability, fast switching speed and low gate drive requirements; the inductor; and an AC coupled rectifier circuit, necessary to prevent problems in the case of OLED pixel shorts such that the intrinsic load voltage is less than 24V. The combination of the selected microcomputer and FET provides an extremely current consumption means of implementing the controller, thereby minimizing the power requirements for this aspect of the circuit.

When powered up, the circuit functioned as expected. However, efficiency measurements showed that instead of achieving >90% efficiency, the actual efficiency was only about 78%, clearly well below our design goal of 92%. It was noted that the inductor was heating, and found that the inductors were operating in a way that was possibly pushing the bounds of their capabilities (inductor losses are approximately linearly a function of frequency, but a function of slightly more than the square of peak flux density -- related to the product of the inductance and current). It was found that the lower the value of the inductor, the higher the losses were and as the value of the inductors increased, the losses decreased as the inductor value increased -- exactly contrary to expectations set by the inductor manufacturers. The highest measured efficiency using commercially available inductors was 86%. A custom made inductor that had large enough core and air gap to avoid potential saturation effects was employed. However, when installed, it too heated up. It was noted that the in circuit Q was about only half of the out of circuit Q. This indicated that the probable problem was due to eddy currents created in the ground plane upon which the inductor was installed.

As a result of these experimental results, the PCB has been redesigned to eliminate the ground plane beneath the inductor. It was designed with the possibility to use two inductors in series, if that is necessary. Finally, output filter capacitors were made larger, in the case that it is found best to run the converter at a low frequency (e.g., 100KHz) instead of its design frequency of 500KHz.

Using the combination of the newly designed fixture and lens, improved OLED device structure and the redesigned OLED drivers, we have developed two phosphorescent OLED (PHOLED™) luminaire systems marking the completion of Milestone 5 of our ceiling luminaire project. See Figure 21.

Figure 21: OLED lighting luminaires mounted in a ceiling system. Each luminaire is comprised of four 15cm x 15cm lighting panels mounted in outcoupling enhancement lenses.

Each luminaire with overall dimensions of approximately 15cm x 60cm is comprised of four 15cm x 15cm OLED lamps. Each lamp consists of a PHOLED lighting panel, outcoupling enhancement lens and a mounting frame for attachment of the lamp to the ceiling fixture. The lamps are driven by an OLED driver mounted in the ceiling fixture. The drive electronics efficiency was measured at 88%.

Due to the large size of the luminaire, we could only predict its efficacy by characterizing the individual luminaire components. Results are shown in Table 4, and for our high efficiency configuration we have achieved a combined power supply and lamp efficacy of 51 lm/W. Lifetime, extrapolated from pixel data, predicts a panel lifetime, LT70 of 10,000 hours. These results are for 40 lumen output per panel, representing 160 lumens per luminaire.

	15cm x 15cm PHOLED Lighting Panel First Result
Panel Efficacy	58 lm/W
Driver efficiency	88%
Overall Efficacy	51 lm/W
CRI	84
1931 CIE	(0.432, 0.436)
Light Output	40 lumens per panel
LT70	Extrapolates to 10,000 hrs
CCT	3320 K

Table 4: Summary of the performance of the 15cm x 15cm PHOLED Lighting Panel

I. Phase 5. (Months 13-24) Commercialization implementation

As part of this project, we developed an OLED lighting commercialization roadmap. This roadmap addressed establishing manufacturing, marketing, sales and distribution channels for volume commercialization of OLED lighting products. The full commercialization roadmap is submitted as a separate document.

Figure 22 shows a synopsis of our roadmap for the commercial building market. The highlighted quality drivers from our focus group research are listed in the upper left of the roadmap. These drivers are the major contributors to what the lighting community considers good quality lighting. They must not be over looked, and their measures should be presented in a clear and transparent manner. The lighting community is skeptical about new technologies, and false or even exaggerated claims will be identified and will have a detrimental effect on their perception of a product.

The bottom of the roadmap marks the progression of time, above that is the estimated manufacturing cost of OLED lighting and the amount of investment in capital and expense at each time period. Above that are blocks containing the status of each channel: Manufacturing (MF), Marketing (MK), Sales (S), and Distribution (D). Then finally there are three blocks.

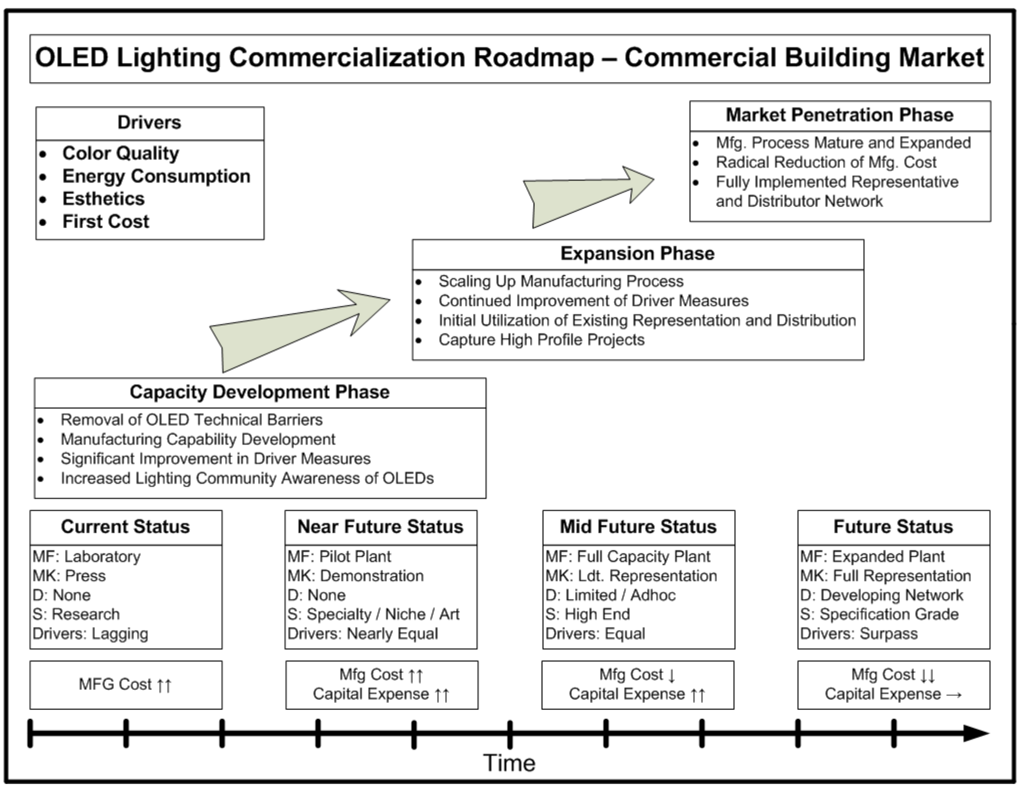

Figure 22 - OLED Lighting Commercialization Roadmap

Each block represents a phase of commercialization; Capacity Development, Expansion and Market Penetration.

Starting at the Current Status, OLED Lighting is being manufactured in the laboratory, most of the marketing is being conducted via press releases highlighting progress in development, there is no distribution, and most sales are research orientated and the driver measures lag behind the established light sources (fluorescent) in the market. This is the beginning of the Capacity Development Phase. Focused effort at removing the remaining technical barriers specific to OLED Lighting must be applied, and fully funded. In parallel a pilot plant should be developed to increase the manufacturing capability of OLED lighting. In the pilot plant the necessary equipment and processes for volume manufacture of OLED are to be developed. As technical barriers are removed in the laboratory, these solutions should be further developed and transferred to the pilot plant. Parallel development of manufacturing capability with technical barrier removal and quality lighting diver improvement, is necessary to reduce the cost of OLED lighting as it approaches equity with the quality measures of established light sources.
By the end of this phase, OLED lighting will be manufactured in its own pilot plant, and will be marketed not only in the press but also through major demonstrations and installations. Sales in specialty, niche and even as art should be pursued and the Lighting Quality Drivers will be approaching parity with the established lighting sources. At this stage OLED may be much more expensive than established sources and the amount of investment will still be very large.

The next phase, the Expansion Phase, is where the manufacturing process is scaled up to start to produce volume level of product. The quality drivers will continue to be improved; with technical improvement still occuring in the research laboratories, while additional improvements will also be developed at the manufacturing plant itself. At this stage, OLEDs will be seen as a viable product alternative by the lighting community and the need for limited representation occurs, and there may also be the need for limited or ad hoc relationships with lighting distributors. It is at this phase where high profile projects should be pursued.

At the Mid Future there will be a full capacity plant, limited representation, limited or ad hoc distribution, sales will target high end spaces and the quality divers will be equal to the established light sources. It is at this stage where manufacturing cost reduction accelerates, and this will require large investment.

The final phase on the roadmap is the Market Penetration Phase. Here the manufacturing process is mature and expanded; this radically reduces the manufacturing cost of OLED lighting. A fully implemented representative and distributor network has been established and sales will be across the spectrum from high end to specification grade.
By the end of this phase OLED lighting will exceed the established light sources in all quality measures and will be set to advance to the next stage (off this roadmap); OLED Lighting in radically different shapes and form factors.

J. Conclusion

During this 2 year program, we further developed our high efficiency white Phosphorescent OLEDs from the first milestone, achieving a 65 lm/W single pixel to the final milestone, achieving 58 lm/W on a 6 inch lighting panel, a world record for OLED lighting performance. Working closely with team member, Armstrong World Industries, a lighting luminaire for the OLED lamps was designed and fabricated to be integrated into their novel TechZone open architecture ceiling systems. Each luminaire with overall dimensions of approximately 15cm x 60cm is comprised of four 15cm x 15cm OLED lamps. Each lamp consists of a PHOLED lighting panel, outcoupling enhancement lens and a mounting frame for attachment of the lamp to the ceiling fixture. The lamps are driven by an OLED driver mounted in the ceiling fixture.

As a result of advancements gained under this program, the path to move OLED lighting panels from development into manufacturing has been realized. While first products into the market place will be glass based, a portion of the development effort will work on flexible substrates. Under this program, the development in flexible lighting panels was evident with the milestone achievement of the delivery of a lighting panel built on flexible steel foil.

Although the metrics we set for this program were extremely aggressive, the performance we achieved and report, represents a very significant advancement in the OLED lighting industry.

K. Recommendations

For OLED lighting to be successful, progress is required both in terms of technical performance as well as commercialization strategy. Technical progress is required for OLED panels to meet the performance requirements for solid-state lighting, panel manufacturing needs to be established in the U.S., and luminaire manufacturers need to have access to these panels to start manufacturing OLED lighting products. UDC has been actively engaged in all these activities to advance the technology towards commercial viability. See Figure 23 for a summary of the development path for OLEDs to penetrate the marketplace.

Key technical issues to address include: further improving device efficacy, further improving device lifetime at higher luminances, and scaling the technology from pixels to larger area (e.g. 15cm x 15cm) OLED lighting panels. This work will require the development of thin outcoupling enhancement solutions which can at least double the light output of an OLED lighting panel, without adding significant thickness to the panel. Once OLEDs meet specific minimum performance objectives (panel efficacy > 80 lm/W, panel LT70 > 25,000 hours at 6,000 lm/m^2) it is recognized that they could then be widely launched in commercial products. This has been the focus of our recent DOE funded programs.

To this end UDC (with partial support form the DOE) has partnered with Moser Baer Technologies (MBT) to transfer our PHOLED technology to a pilot OLED lighting manufacturing line MBT are establishing in the U.S. This will enable the U.S. manufacture of OLED lighting panels using UDC's phosphorescent OLED technology, advanced with partial DOE funding. Luminaire manufacturers will then have access to high performance PHOLED lighting panels. Finally we have also established programs with lighting companies to seed the market with product prototypes to accelerate the launch of OLED lighting products. For example, our work in this program with Armstrong Industries to develop a prototype ceiling luminaire which snaps into Armstrong's TechZone ceiling system providing the necessary infrastructure for the use of energy saving OLEDs for ceiling luminaires. We have also been developing prototype under-cabinet OLED lighting with the goal of working with a major U.S. lighting company to commercialize these products.

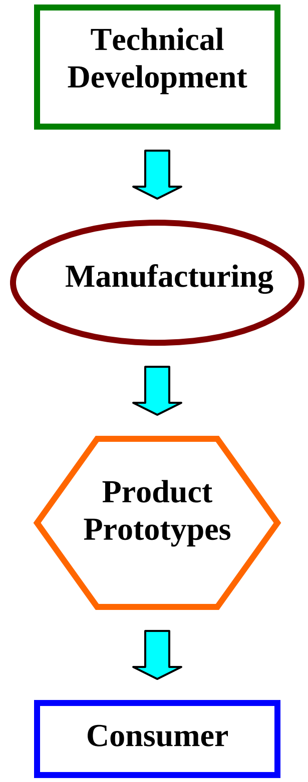

Figure 23: The development path for OLED lighting to penetrate the marketplace

We believe that OLED lighting represents a novel, appealing and energy saving technology for solid state lighting. It offers the potential for significant job creation in the U.S. through the establishment of a new technology and manufacturing base, offering to reduce our dependence on foreign energy sources. As such we believe it is important for the DOE to maintain or increase their funding of this critical technology to ensure that the U.S. can fully benefit from its ability to provide safe and efficient lighting for our future.