FINAL TECHNICAL REPORT

"Novel Smart Windows Based on Transparent Phosphorescent OLEDs"

Submitted by

Universal Display Corporation

375 Phillips Blvd.

Ewing, NJ 08618

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Principal Investigator:- Dr. Brian D'Andrade (Senior Scientist)

Tel:- 609-671-0980 x292

Fax:- 609-671-0995

bdandrade@universaldisplay.com

Subcontractor:- Princeton University

Principal Investigator:- Prof. Stephen Forrest

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Abbreviations and Acronyms

Alq_3	Aluminum-tris(8-hydroxyquinolate)
BCP	2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline
BL	Blocking layer
CCT	Correlated Color Temperature
CIE	Commission Internationale de l'Eclairage
CRI	Color Rendering Index
DOE	Department of Energy
EL	Electroluminescence
EML	Emissive Layer
ETL	Electron Transport Layer
EQE	External Quantum Efficiency
FPt	Platinum(II)(2-(4',6'-difluorophenyl)pyridinato-N, C2')(2,4-pentanedionato)
HID	High Intensity Discharge
HIL	Hole Injection Layer
HOMO	Highest Occupied Molecular Orbital
HTL	Hole Transport Layer
ITO	Indium-tin-oxide
LUMO	Lowest Unoccupied Molecular Orbital
mCP	1,3-N,N-dicarbazole-benzene
NIST	National Institute of Standards and Technology
NPD	naphthyl-phenyl-diamine
OLED	Organic light emitting device
PEDOT/PSS	Poly(3,4-ethylenedioxythiophene)/poly-(styrenesulfonate)
PHOLED™	Phosphorescent organic light emitting device
PL	Photoluminescence
Princeton	Princeton University
RGB	Red, Green and Blue
SBIR	Small Business Innovation Research
TPA	Triphenylamine
UDC	Universal Display Corporation
USC	University of Southern California
WOLED	White OLED
λ	Wavelength

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Executive Summary

In this program, Universal Display Corporation (UDC) and Princeton University developed the use of white transparent phosphorescent organic light emitting devices (PHOLEDs™) to make low-cost 'transparent OLED (TOLED) smart windows,' that switch rapidly from being a highly efficient solid-state light source to being a transparent window. PHOLEDs are ideal for large area devices, and the UDC-Princeton team has demonstrated white PHOLEDs with efficiencies of >24 lm/W at a luminance of 1,000 cd/m^2.

TOLEDs have transparencies >70% over the visible wavelengths of light, but their transparency drops to less than 5% for wavelengths shorter than 350 nm, so they can also be used as ultraviolet (UV) light filters. In addition to controlling the flow of UV radiation, TOLEDs coupled with an electromechanical or electrically activated reflecting shutter on a glass window can be employed to control the flow of heat from infrared (IR) radiation by varying the reflectance/transparency of the glass for wavelengths greater than 800nm. One particularly attractive shutter technology is reversible electrochromic mirrors (REM). Our goal was therefore to integrate two innovative concepts to meet the U.S. Department of Energy goals: high power efficiency TOLEDs, plus electrically controlled reflectors to produce a 'smart window.'

Our efforts during this one year program have succeeded in producing a prototype smart window shown in the Fig. I, below. The four states of the smart window are pictured: reflective with lamp on, reflective with lamp off, transparent with lamp on, and transparent with lamp off. In the transparent states, the image is an outdoor setting viewed through the window. In the reflective states, the image is an indoor setting viewed via reflection off the window.

We believe that the integration of our high efficiency white phosphorescent TOLED illumination source, with electrically activated shutters represents an innovative low-cost approach to conserving energy, and such innovative approaches are required to drive towards the DOE's goal of a 50% reduction in electric lighting consumption by 2020, and an energy efficient building. Furthermore, the team of UDC and Princeton University is ideally suited to develop and demonstrate this technical approach because of our recognized expertise in the fields of PHOLED and OLED technologies. Several benefits to the public are listed below.

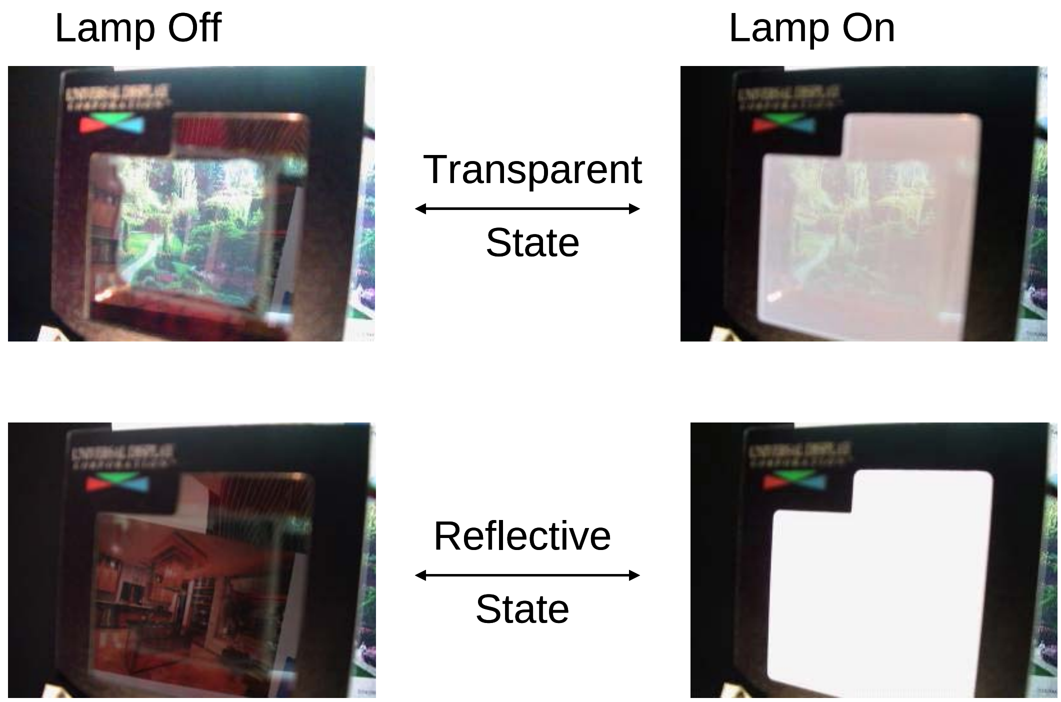

Figure I. These four pictures show the four states of the 'Smart Window'. In the transparent state, one views an outdoor setting with the lamp either on or off. The lamp is dim in this case to show that the window is still transparent, but it can be made brighter. In the reflective state, one views an indoor setting with the lamp off, and uniform white emission with the lamp on.

Achievements

- Successfully demonstrated the first integrated window technology that combines an electrochromic mirror and a light source that is transparent in the off-state.
- Developed electronic driver system to operate smart window.
- Worked closely with DOE to keep program focus.
- Initiated new relationship with Rockwell Scientific to build smart window.
- Completed program on time.

Energy Benefits

Because lighting is a major component of energy consumption in the U.S., new white lighting technologies are of considerable national interest as demonstrated by the goals of the U.S. DOE Solid State Lighting Program. In addition, advances in building envelope technologies to reduce energy consumption are also receiving significant attention. The work described in this proposed program can address both sets of goals – by demonstrating the use of a high-efficiency, transparent PHOLED light source in an architectural window component.

While the concept of smart windows using polymer dispersed liquid crystal (PDLC), electrochromic and suspended particle device (SPD) technologies have been under development for years, the concept of integrating TOLEDs into architectural window glass creates new opportunities for significant gains in *lighting* energy efficiency.

The basis of this opportunity comes from the fundamental discovery and development of UDC's phosphorescent and transparent OLED technologies. TOLEDs have the potential to achieve a power efficiency of 100 lm/W light source within the next five to ten years. As such, white TOLEDs can reduce the need for less efficient incandescent and fluorescent light fixtures.

The use of TOLED lighting will also engender better use of lighting through better architectural and product designs, improved lighting usage behavior by end users, and superior quality of the overall building environment. They may also possibly be constructed so that they provide better heat gain and lighting control during the day and evening akin to the properties of conventional EC window technology. These advantages can all translate into additional energy savings.

The energy saving benefits associated with white TOLEDs can be truly significant. While it is premature to understand well the potential penetration of this technology into architectural windows, **0.28 quads** can be saved if this technology penetrates 10% and 20% of all incandescent and fluorescent lights in residential and commercial buildings, respectively. This calculation is based solely on more efficient lighting, and does not factor in the second order benefits of this more efficient form of lighting.

In another comprehensive study presented by David Garman, Assistant Secretary, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy late lst year, energy consumption for lighting is projected to continue to grow over the next decade from 8.2 quads in 2003 to as much as 10.5 quads by 2025. With the introduction of solid state lighting such as OLEDs, energy consumption can be reduced by 1 to 3 quads by 2025 depending on the level of investment in this area over the coming years. The work in developing white TOLEDs for windows can make a significant contribution in this area and leverage the work initiated under the Solid State Lighting Program.

Environmental Benefits

The energy savings benefits of this technology will also translate into significant environmental benefits. Less electricity consumption means lower consumption of non-renewable resources as well as less greenhouse gas, water/air pollution and waste disposal generation. Based on the energy savings calculated above, the carbon saving benefits can conservatively be **4.4×10^6 metric tons** annually.

Economic Benefits

The market potential for TOLED smart windows is tremendous. This is based on a $10 billion lighting market that thirsts for more efficient forms of lighting as well as an $8.2 billion US flat glass market that continues to look for more efficient building envelope technologies. If TOLEDs can penetrate 10% of this market (based on square footage) at $10 per square foot (the target price for EC smart windows), this technology alone could be an **$8 billion market.**

Introduction

Developing more power efficient lighting sources is critical for national and global economic and environmental wellness. Within the past 30 to 50 years, little progress has been made in improving the energy efficiency of conventional sources of light, with efficacies for incandescent lights in the range 10 – 20 lm/W, and for fluorescent lamps 30 – 90 lm/W. Moreover, about 70% of the energy used by these sources is wasted as heat. It is predicted that, without more-efficient lighting technology, the total energy consumed by lighting in the U.S. is expected to increase from the current 8.5 Quads to approximately 10.5 Quads by 2025. As a result, new more energy-efficient lighting technology is sought.

There are two key emerging technologies that have been identified as potentially offering significant gains in energy efficiency as well as, at the same time, providing other novel performance attributes that are desired for general lighting. These technologies are: 1) inorganic Light Emitting Diode (LED) and 2) organic light emitting diode (OLED).

These technologies are both "solid-state" but, otherwise, have very distinct attributes that serve complementary target applications. For example, LEDs are relatively expensive *point* light sources that may compete well with incandescent bulbs principally in out-door high brightness lighting (i.e. stadium and billboard lighting), traffic lights, flashlights, headlamps and table lighting. By comparison, an OLED, potentially an inexpensive large-area *diffuse* source, will compete most directly with conventional diffuse lights and, to a lesser extent, with inorganic electroluminescent (EL) lamps in diffuse lighting, e.g., backlights, interior signage and, ultimately, general illumination.

OLED products are presently being sold in the flat panel display market where tremendous progress is being made in device stability and efficiency, so the potential to meet the needs of the general lighting industry is very promising based on current products. In addition to targeting such conventional lighting applications, OLEDs have attributes that provide the possibility of opening up new market applications such as *'smart windows'*, see Fig. 1. This is the subject of the work that was performed under this contract.

OLEDs can be formed on very large area surfaces such as building windows; hence, one may be able to take advantage of all the available window space and incorporate a light source for a room. Additionally, the control of electromagnetic radiation across a window could enable cost savings in terms of heating and cooling of rooms. UDC's smart window incorporates our proprietary transparent OLED (TOLED) [1]technology together with an electrochromic system to take advantage of window space for lighting and energy savings for heating and cooling.

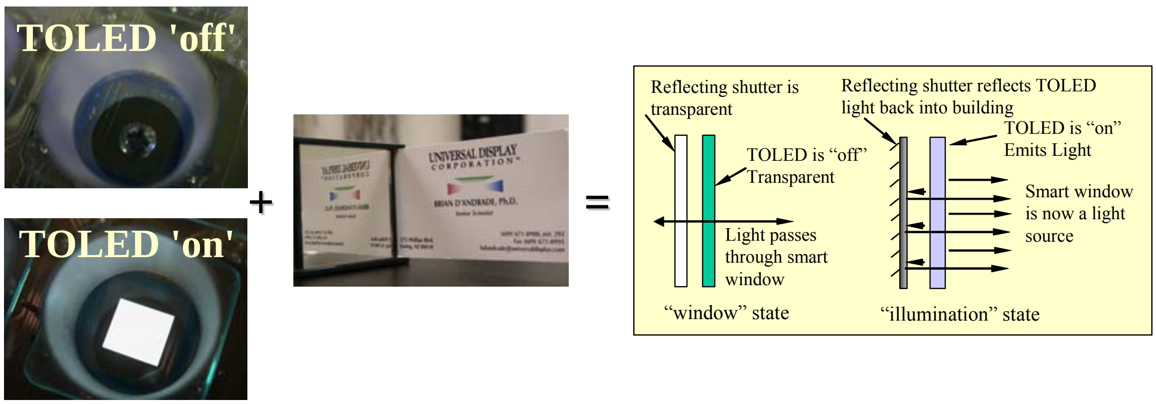

Figure 1. Our goal during this program was to combine a TOLED with an electrochromic mirror.

The proposed device shown in Fig. 1 utilizes a novel advantage of OLEDs over LEDs, which is the ability to make TOLED light sources which can be >70% transparent over the visible spectrum, and to fabricate devices that have very large areas. Thus, OLED technology enables novel and innovative devices such as 'smart windows', which offer significant crosscutting advantages due to their dual usage both as a light source and as a fast response time shutter. This novel device can be operated as both a high efficiency white light source, and as an electrically activated window shutter that controls the flow of radiant energy into and out of buildings.

This concept is demonstrated with our model house containing TOLED windows shown in Fig. 2. These smart windows address two issues simultaneously: building lighting and building heating/cooling. It is unlike any other currently manufactured product, so its technical superiority is difficult to gauge. However, the light source component of this smart window has the potential to achieve >100 lm/W efficiency, which is significantly higher than most currently available lamps. In addition, the development of a smart TOLED window will leverage additional work being carried out under new DOE solid-state lighting initiatives to develop low cost high efficiency OLED technology for general illumination purposes. UDC is also currently working closely with a number of partners including PPG Industries to commercialize phosphorescent OLED technology, and if this smart window program is successful, it is likely that these partnerships will be expanded to include their commercialization.

Figure 2. Mock prototype "House of the future" built by UDC containing TOLED sky lighting and windows. Left picture: At night, the skylight and windows turn on and can emit over a range of 'white' colors from warm to cool white. Right picture: During the day, the TOLEDs are off and transparent, so the windows and sky light are transparent.

Our goal was to integrate two innovative concepts (see Fig. 1) to meet the U.S. Department of Energy goals: high power efficiency TOLEDs, plus electrically controlled reflectors to produce a 'smart window.' At the completion of this 1-year program, we proposed to demonstrate the concept of a TOLED smart window with a prototype 1" × 1" smart window with an efficiency exceeding 20 lm/W at 1,000 cd/m^2 in the 'on' state and a transparency across the visible of 75% in the 'off' state.

Background

Universal Display Corporation (UDC) is a world leader in the field of organic lighting emitting materials, device, and process research and development. UDC has a team of over 30 scientists and engineers focusing in these areas, and a longstanding exclusive research program with Professor Stephen Forrest and his research team at Princeton University; additionally, Professor Mark Thompson and his team at the University of Southern California (USC) are significant contributors to PHOLED research. Today, UDC and its research partners are recognized as pioneers in the area of organic electronics research, and their development for commercial applications. For the past seven years, the team has focused exclusively on developing state-of-the-art OLED technology.

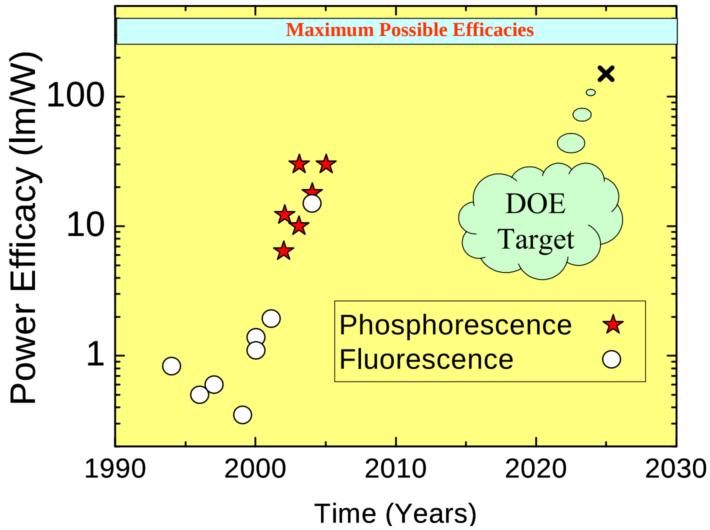

Figure 3. Plot shows white OLED power efficacy over the last decade, and the U.S. Department of Energy's lighting system efficacy goal. PHOLEDs are the most efficient OLEDs.

Key breakthroughs include 1) highly power-efficient phosphorescent OLEDs (PHOLEDs) [2]. 2) optically transparent electrodes and top emission devices (TOLEDs) [3], 3) OLEDs on flexible substrates (FOLEDs) [4], and 4) organic vapor phase deposition (OVPD) [5] for organic device manufacturing and future applications with high throughput roll-to-roll processing of organic electronics.

Recently, we have demonstrated white lighting panels consisting of orange, green and blue stripes that have external efficacies of 30 lm/W, and that emit >100 lm on a 6"× 6" substrate [6]. Figure 3 gives a timeline of the increase in the power efficiency of white OLEDs and 30 lm/W is at the top in 2005. These panels were measured by NIST to ensure accuracy of the measurement, and they represent a milestone in the timeline of PHOLED efficacy. UDC has pioneered the Stripe PHOLED panel technology, which has numerous advantages over current methods for room illumination. First, its high efficiency and the ability to adjust color balance (independent of light intensity) make phosphorescent OLEDs a viable alternative to fluorescent bulbs. Furthermore, the compatibility of OLEDs for use on flexible substrates, e.g. plastic or metal foil, 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 flexible 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.

PHOLED Technology. Since fluorescent OLEDs (small molecule) were first invented by Tang et al. in the 1980s [7], tremendous improvements in all aspects of device performance have been made. The basic principle of OLED operation is that under forward bias, electrons and holes are injected into the organic films and combine to form excitons. The excitons subsequently undergo radiative recombination to generate light. The molecular excited state, or exciton, can either have a total spin of S=0 (singlet state) or S=1 (triplet state). To a first approximation, 25% of generated excitons are in the singlet state, and 75% in the triplet state. As spin conservation applies to photon emission, only singlet excitons lead to optical emission.

Representing a major breakthrough in OLED efficiency, Princeton and USC first reported a new mechanism, based on phosphorescent dopants in OLEDs in 1998 [8]. Today, the team is developing this technology for flat panel displays as well as white devices for lighting [9, 10, 11]. These phosphorescent dopants contain a heavy metal atom that facilitates the mixing of singlet and triplet states, allowing singlet to triplet energy transfer through intersystem crossing (ISC), and that enables the triplet states to radiate. Therefore, in phosphorescent devices, 100% of the excitons can potentially produce optical emission, in contrast to only approximately 25% in conventional fluorescent devices. ***Our team's invention and development of phosphorescence is a key technology that will enable OLEDs to become an efficient and viable general illumination light source. Today our PHOLED technology is acknowledged as a critical element to the success of OLEDs for flat panel display applications.***

Summary of Program Tasks

Our objective in this work was to develop a novel low cost means of producing a 'smart window' that is transparent in one state, a solid-state phosphorescent OLED light source in another state. When on, the white TOLED will enable very high conversion efficiencies (up to > 20 lm/W when combined with optical outcoupling enhancements), and when off, the 'smart window' will be >70% transparent.

The overall program consisted of four tasks, and each task took approximately 3 months to complete.

Task 1 (Months 1 - 3)

The objective of this phase was to evaluate various technologies that change their reflectance upon being electrically activated. Two desired characteristics of the electrochromic technologies that we reviewed were power consumption, and compatibility with TOLEDs. We found that Rockwell Scientific reversible electrochromic mirror (REM) was the most suitable for this program.

Task 2 (Months 4 - 6)

The principle objective of Phase 2 was to design all the electronics and masks sets required to build a TOLED that can be integrated with the reflective technology chosen in Phase 1. The white TOLEDs characteristics should have a power efficiency >20 lm/W at 1000 cd/m^2, and a transparency of 70%.

Task 3 (Months 7 – 9)

The objective of Phase 3 was to establish a process to integrate the TOLEDs with the reflector. Also, the electronic controls were completed during this phase, for the final demonstration.

Task 4 (Months 10 - 12)

The objective of Phase 4 was to prepare the final prototype 'TOLED smart window'. This involved fabricating TOLEDs, assembling the components of the 'smart window' based on the work completed in Phase 3, and characterizing the smart window in terms of color rendering index, CIE color coordinates, transparency and power efficiency.

TASK 1.0 – Purchase and evaluation of electrically activated reflectors.

We evaluated appropriate electrically activated shutters that have a high reflectivity (>50%) in one state and a high transparency (>70%) in a second state, and that are compatible with our thin film technology. There were several products that we examined: polymer dispersed liquid crystals, cholesteric liquid crystals, speedglass, and reversible electrochromic mirror.

Polymer dispersed liquid crystals (PDLC) can be switched from a transparent state to an opaque state. The optical transmission across the visible of the PDLC switches from ~65% in the clear state to <1% in the opaque state, and the reflectivity across the visible of the PDLC changes from ~30% in the opaque state to ~10% in the clear state. Furthermore, the transmission in the infrared region from 800 nm to 1700 nm is reduced from ~50% in the clear state to ~20% in the opaque state, so there is tremendous potential to control the flow of infrared radiation across the window.

The reflectivity across the visible is diffusive instead of specular, so the sheet of glass appears milky white in the opaque state instead of mirror-like. The diffusive reflectance property is more suitable for a window than a specular reflector, because it substantially reduces glare, which is not a desirable property of a windows.

Cholesteric LC panels are bistable and can be switched between an opaque state and a clear state by applying a transient electrical pulse. The bistable nature of cholesterics means that very little electrical power is consumed, which is ideal for a smart window application. Figure 4 shows the optical transmission and reflection at 20° incident angle for both states of the cholesteric LC. These measurements were taken using an ellipsometer located in Princeton University. The ellipsometer has very accurate alignment capabilities that prevent changes in the beam path length that causes errors in these sorts of measurements; it can also accommodate the large samples, and it can accurately measure specular reflection at several angles.

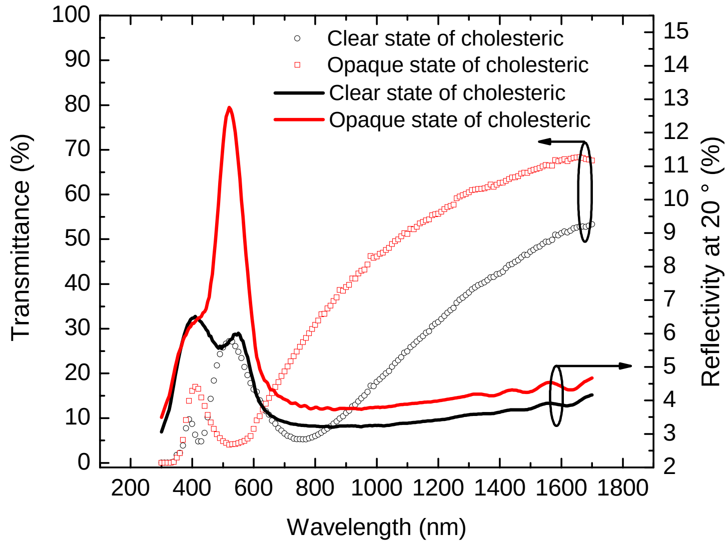

Figure 4. Transmittance and Reflectivity of both states of a cholesteric LC panel are plotted.

The transmittance spectra in the clear and opaque states are given by the black and red circles, respectively, and the reflection spectra in the clear and opaque states are given by the black and red lines, respectively. In the opaque state, the absorption of near infra-red and infra-red radiation is 20-30% lower than in the clear state. However; the panel reflects more light, in the opaque state, across the visible as shown by the peak (80%) in reflectivity at 520 nm.

Morgan Tench suggested that it may be possible to incorporate Rockwell's reversible electrochromic mirror (REM) with Universal Display Corporation's TOLED. The reflectance spectra in the off and on states of the REM are shown in Fig. 5 [12]. The REM device is comprised of a gel electrolyte sandwiched between a thin Pt nucleation layer and a counter electrode. The reflectance and transmission is controlled electrically, and UDC investigated monolithically fabricating the REM and TOLED when we received a sample from Rockwell Scientific during this program.

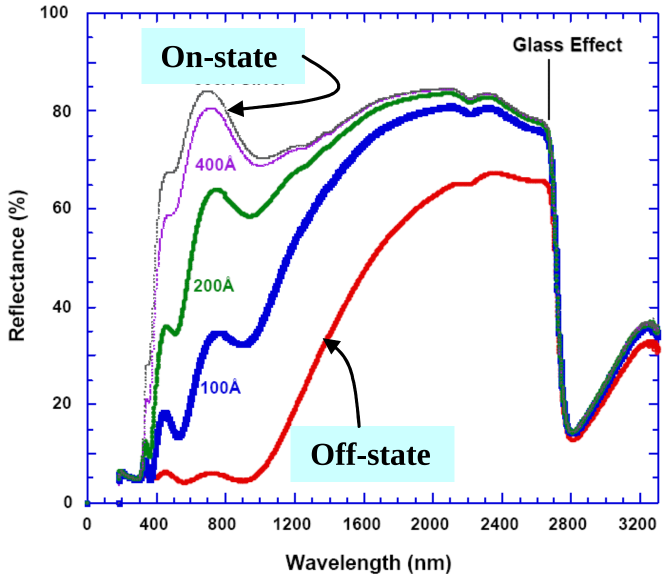

Figure 5. Reflectance spectra of reversible electrochromic mirror versus the thickness of silver nucleation. The reflectivity of the REM increases with Ag thickness [12].

Our objective in this work was to develop a novel low cost means of producing a 'smart window' that is transparent in one state, a solid-state phosphorescent OLED light source in another state, and can also control heat flow by adjustments of its reflectance. During Phase I, we tested the REM optical characteristics change upon application of an electrical signal, and the REM seems to be the best choice from the deliverable. The REM device was operated here at UDC, and Fig. 6 shows the REM in the reflective and transparent states.

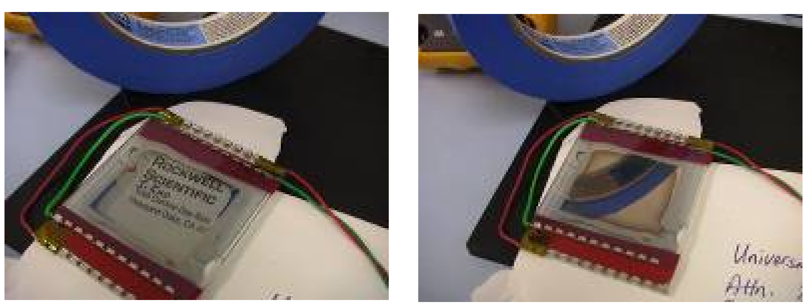

Figure 6. Reversible electrochromic mirror was switched using electronics developed in-house at Universal Display Corporation.

Task 1 Summary

Overall, the team's efforts on obtaining an electrochromic system were successful, and we managed to establish an informal relationship with Rockwell Scientific researchers. The REM was selected for the smart window based on the optical properties in the clear and opaque states of the device, and it will be part of the deliverable that we present to the DOE during our final presentation.

TASK 2.0 – Design and fabrication of electrical and mechanical components.

The OLED light sources to be used in the deliverable are approximately 50mm × 50mm squares with a fill factor on the order of 50%, yielding 12 cm^2 OLEDS. Assuming a current density of 10mA/ cm^2, the drive electronics must deliver about 120 mA to each light source. A prototype electronics board is shown below in Fig. 7.

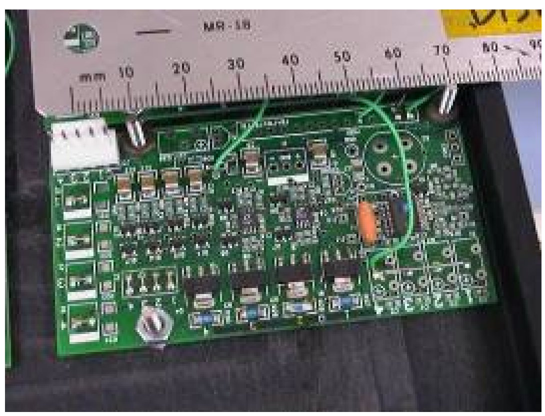

Figure 7. The board has four constant current outputs, all of which are adjusted in unison with a potentiometer. The circuit topology is linear with common cathode, and the board is powered from a common 120V/1A wall plug. An optional micro-controller is part of the circuit for future applications such as digital dimming.

Figure 8 shows a smart window prototype that is battery powered and fully portable PHOLED that was fabricated at Universal Display Corporation in Ewing, NJ. This is a fully portable demo system that is battery powered. The team is able to couple this system to any electrochromic device that is used for the final deliverable. Alternatively, we can use a smaller substrate size if the electrochromic system is too small for this device size. During this program, we developed process conditions to further improve the yield of these types of devices. The new processing techniques reduced electrical shorts, increased the yield of devices, and increased the useable lifetime of such a large area PHOLED.

Figure 8. Portable white PHOLED that was coupled to electrochromic device for final deliverable. The device has an area of 25 cm^2 and is only ~1cm thick.

The following are the drive specifications for the REM device from Morgan Tench at Rockwell Scientific.

1) To switch REM to mirror state, apply -90 mV to the cell, limiting magnitude of current to 4 mA. Allow mirror to form and then disconnect from voltage source.

2) To switch REM to clear state, apply +80 mV to the cell, again limiting magnitude of current to 4 mA. Allow cell to clear, and then disconnect from voltage source.

The block diagram of the circuit, shown in Fig. 9, works as follows. Digital control signals are provided by a flash programmable microcontroller. To form mirror state, a 4 mA current source is switched ON, and this current source drives the output transistor of a voltage follower circuit formed by U2B, Q3. The output voltage is derived from a 5V microcontroller output, S4, and set by a resistor divider formed by R6, R3 to 90 mV. Simultaneously, Q11 is turned off and Q10 is turned on. Thus the REM cell has -90 mV applied to it and this voltage is current limited to 4 mA by the current source formed by U2A, Q1. In order to apply the 80 mV clearing voltage, S4 is turned off, Q11 turned on, Q10 off, and voltage is supplied by voltage follower formed by U2B, Q2. The REM cell may be open-circuited by turning off microcontroller outputs S1, S2, S3, S4 when the transition has occurred fully. This circuit is similar to an H-bridge motor drive circuit where the pull-up legs are current limited voltage sources and the pull-down legs are simple switches. The user sets the desired REM state with switch SW1, and the microcontroller sets all the other control outputs accordingly. The microcontroller can also time out and then effectively disconnect the REM cell after a programmed time out period.

The TOLED is driven with a constant current source with periodic reverse bias voltage pulses which help to clear potential shorts. The user turns the TOLED ON/OFF via SW2. The electrical schematic is shown in Fig. 9. This system was assembled as part of the final deliverable consists of drivers for the REM and the TOLED in a single unit.

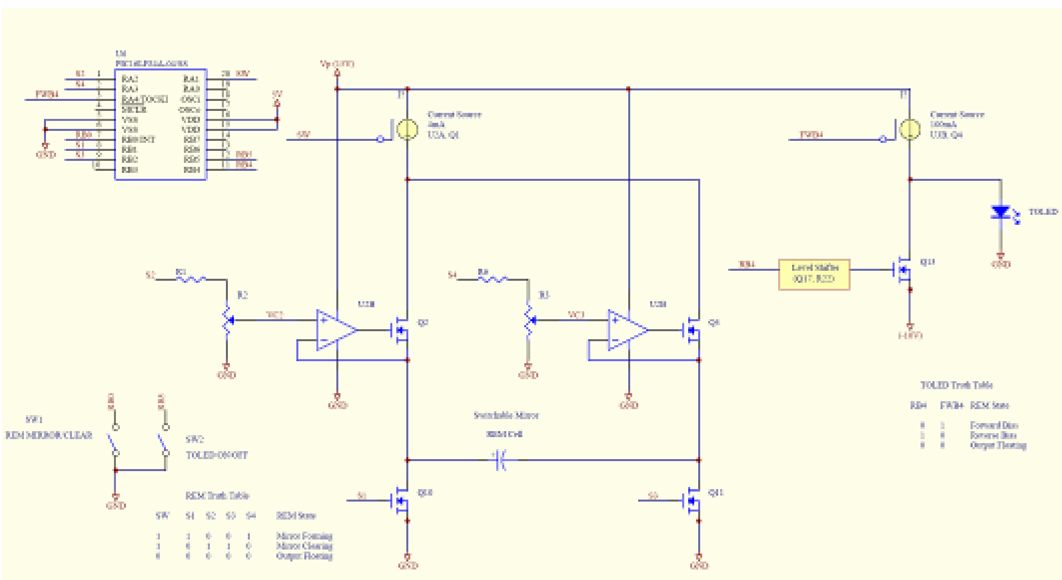

Figure 9. Electrical schematic of driver electronics for REM and TOLED Smart Window device.

Task 2 Summary

The electrical components were essential to this program. UDC has an in-house electronics designer, so the external drive components were designed and fabricated on time and with superb skill. A complete electronic driver system was delivered along with the smart window.

TASK 3.0 – Coupling, packaging and characterization of system.

The REM device and the WOLED have to be optically coupled and there are three requirements for an adhesive that will be needed to perform this task: good bonding strength, fast curing without heating, and index matched to glass. We investigated the use of UV-curable and thermally curable epoxies.

The OLED light sources to be used in the deliverable are roughly 50mm × 50mm squares with a fill factor on the order of 50%, yielding 12 cm^2 OLEDS. The OLED has to be mechanically attached to an electrochromic device, which will be fabricated on glass. One option that was explored to connect the two devices is the use of UV-curable epoxy that is index matched to glass i.e. a UV curable epoxy with an index of refraction of 1.5. Both the OLED substrate and the electrochromic substrate should be joined to reduce optical losses and interference effects, so an epoxy that is index matched to glass should be ideally suited for that purpose.

We investigated the suitability of UV-curable cements: Lens Bond Type SK-9 and VTC-2. SK-9 is a single component, modified Acrylate/Methacrylate Photopolymer. This low viscosity liquid polymer is easy to apply and quick to pre-cure. The curing process involves exposure to long wave ultraviolet light (365nm). Its high wetting and low shrinkage combine to give a superior bond, and its very low viscosity liquid practically eliminates air bubble problems. Additionally, SK-9 shows extremely high adhesion to many types of plastics and permits the user to pre-cure the elements in 3-5 seconds using a 4 to 15 watt fluorescent UV light at 1" from the upper element, while full-cure is attained in 1 hour at 1".

Type VTC-2 cement is a single component, water white, ultraviolet curing polymer. Type VTC-2 can be used as an adhesive or a coating material, and cures by exposure to long wave ultraviolet light 365nm. Type VTC-2 exhibits excellent adhesion to glass, ceramics, and various metals, and its high viscosity aids in holding placement on optical fibers being bonded to Grin lenses. Its high viscosity also helps in silk screen pattern cementing

Both cements have >90% transmission over the entire visible spectrum, so we expect low optical losses to be incurred by use of these cements. Given that the polymers are UV-curable, we avoid any degradation of devices that may occur due to heat treatments that is sometimes necessary to cure cements. Both cements have >90% transmission, see Fig. 10, over the entire visible spectrum, so we expect low optical losses to be incurred by use of these cements

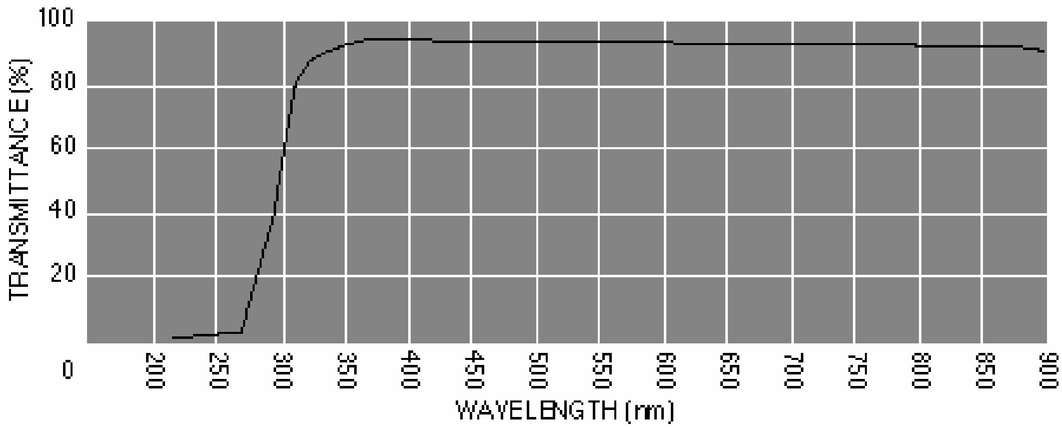

Figure 10. The transmission of the adhesives is shown to be above 90% over the visible wavelengths of light. This characteristic should keep optical losses to a minimum.

Additionally, we purchased thermally curable optical cement from Summers Optical to couple the TOLED to the REM. The cement cures in 45mins at 70°C, which is a processing temperature that is compatible with our PHOLEDs. Our work with UV curable cements eventually revealed problems with our ability to deliver high doses of UV light to the cement, so the cement did not fully cure. The thermally curable glues have almost identical transmission properties to the UV-curable glues.

In addition to fabricating TOLEDs, a white bottom emitting PHOLED was grown to demonstrate the upper limit of efficiency achievable by this technology during this program. A PHOLED has an aluminum cathode which forces emission through only side of the substrate. This is distinctly different from the TOLED which emits from both sides of the substrate. Figure 11 shows the efficiency of the white device that was incorporated into this program

There are several points to note about the characteristics shown. At 1,000 cd/m^2, the power efficiency is 14 lm/W, which corresponds to about 28 lm/W when outcoupling enhancements are attached to the lighting panel [13]. The peak 12.8 % in the external quantum efficiency occurs at high luminance of 1,000 cd/m^2, and the peak in the power efficiency reaches 19 lm/W at a low luminance (forward direction only).

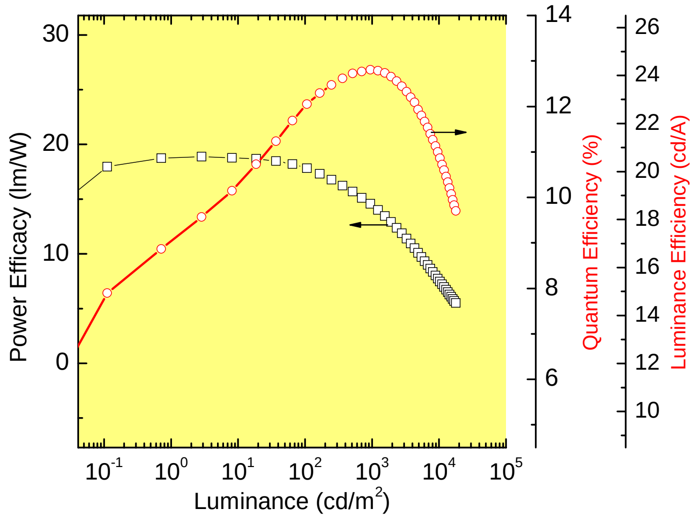

Figure 11. The forward emission power efficacy, quantum and luminance efficiency for a white OLED are plotted. The total power efficiency is estimated to be twice the efficiency shown in this plot.

TASK 4.0 – Fabricate 1" x 1" 'TOLED smart windows'

Figure 12 shows the white TOLED with an OLED Luminaire that will delivered to the DOE at the final presentation. At 20 lm flux output the device has an efficiency of ~9 lm/W, and 10 lm/W at 1.5 lm. At ~10 lm output, the emission from the front and back surfaces of the device is 1050 cd/m^2 and 200 cd/m^2, respectively. The CIE were (0.39, 0.39) and the CRI was 70. The correlated color temperature is 4400 K, which corresponds to a warm white color akin to an incandescent lamp color.

In the final deliverable, we chose to utilize new stable PHOLED materials that result in very good operational lifetimes. The power efficiency was somewhat below the desired specifications. The TOLED light source has a projected lifetime of **>3,000 hrs at 600 cd/m^2** with only a minor chromaticity shift over the operational lifetime of the system. The 1931 CIE chromaticity shift with aging is <= 0.02 for both the x and y CIE coordinates. This represents a tremendous advancement in OLED technology for lighting.

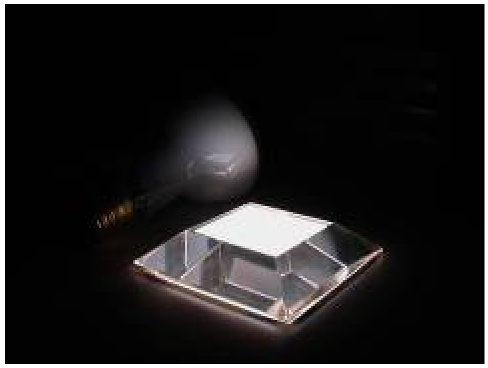

Figure 12. White TOLED with luminaire is shown to emit uniform light across the luminaire.

Additionally, to yield the large area transparent PHOLED, we employed a new transparent cathode consisting of LiF/Al/Ag. This new cathode has a transmission below the specified 70%, but devices have a high yield when fabricated with this cathode. An additional benefit of using this transparent cathode is that more of the light is directed from the OLED directly into the area being illuminated. This lessens the need for a reflective electrochromic mirror on one side of the white TOLED. As mentioned above, the front face of the OLED outputs 5 times the luminance of the other back face.

The full system including the REM and the TOLED is shown in Fig. 13. Our efforts during this one year program have succeeded in producing a prototype smart window shown in the figure below. The four states of the smart window are pictured: reflective with lamp on, reflective with lamp off, transparent with lamp on, and transparent with lamp off. In the transparent states, the image is an outdoor setting viewed through the window. In the reflective states, the image is an indoor setting viewed via reflection off the window.

Task 4 Summary

Overall the deliverable was successfully made; however, a lot more effort needs to be applied to the problem of sputtered ITO induced defects. This represents a significant challenge which we will be overcome with additional internal funding. The target efficiency and transparency of the large area TOLED were not met, because of the trade-off with efficiency/transparency and fabrication yield; however, we successfully complete the demo deliverable that was presented to the DOE project manager after the final presentation. Future work will focus on transparent cathode technology to improve transmission and overcome yield issues associated with the ITO cathode.

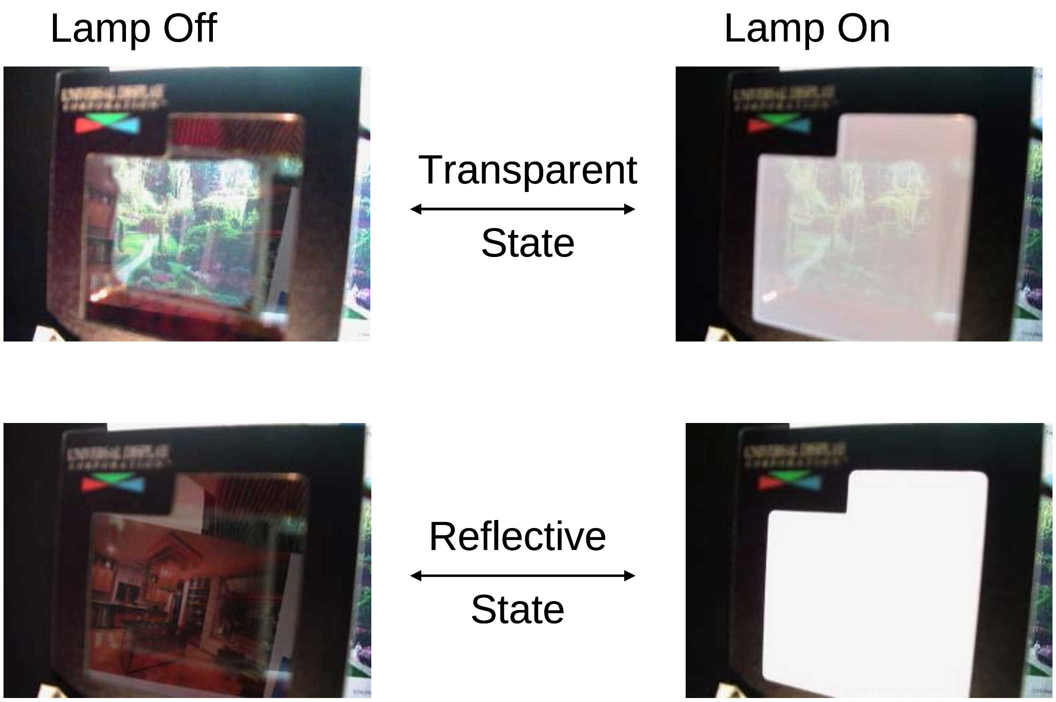

Figure 13. These four pictures show the four states of the 'Smart Window'. In the transparent state, one views an outdoor setting with the lamp either on or off. The lamp is dim in this transparent case, but it can be made to be brighter. In the reflective state, one views an indoor setting with the lamp off, and uniform white emission with the lamp on.

Roadmap for High Energy Efficacy PHOLED lighting sources.

We believe that the DOE's 2015 SSL efficiency target of > 100 lm/W will require the use of PHOLED light sources, and we provide this roadmap to help set performance goals. The following analysis identifies the factors and describes a prospective pathway to achieve >100 lm/W power efficiency. For a lambertian emission OLED source, where V = operating voltage and η_{lum} is luminance efficiency (candela per Amp), the power efficiency (η) and luminous efficiency (η_{lum}) are

$$\eta = \eta_{lum} \cdot \pi / V \qquad (1),$$

$$\eta_{lum} = k \cdot \eta_{Int} \cdot \eta_{Out} \qquad (2),$$

where η_{Int} = internal quantum efficiency (% excitons to photons) and η_{Out} = outcoupling efficiency (a measure of how many generated photons are emitted from the device), and k is a constant dependent on the photopic response of the human eye. Hence

$$\eta = k\, \eta_{Int}\, \eta_{Out}\, \pi / V \qquad (3)$$

As a result, power efficiency is a function of internal quantum efficiency, η_{Int} , light extraction, η_{Out}, and voltage, V. Thus, to improve device performance, advances in these areas are required. To exceed 100 lm/W, (a) 100% internal quantum efficiency, (b) 3.0 V operating voltage at target brightness and (c) 40% outcoupling efficiency (40% external quantum efficiency) must be met. With PHOLED technology, voltage reduction strategies and light extraction enhancements, this efficiency goal is possible by 2010.

(a) 100% Internal Quantum Efficiency

Previous results have shown that for these phosphorescent devices, internal quantum efficiencies approaching 100% have been reported, and external quantum efficiencies of nearly 18% have also been demonstrated. These results have been achieved by discovering highly efficient phosphorescent emitters and implementing device architectures to maximize triplet emission. One such architecture is achieved by the following layer sequence: Anode/Hole Injecting Layer (HIL)/Hole Transport Layer (HTL)/Emissive Layer (EML)/Blocking Layer (BL)/Electron Transport Layer (ETL)/Cathode. A key component of achieving highly efficient phosphorescent OLEDs is to ensure that the electron-hole recombination occurs in the emission layer close to the phosphorescent dopants. The band alignment at the EML/HTL interface, coupled with the low electron mobility of the hole transport layer prevents electrons from leaving the EML, and the incorporation of the blocking layer impedes the diffusion of excitons and holes from leaving the emission zone.

It must be emphasized that the luminance requirement of 800 cd/m^2 for lighting is very similar to that for a full-color active matrix OLED. As a result, the goals for lighting are in line with development targets for flat panel displays (FPDs). At this modest brightness, the PHOLEDs are still operating close to their maximum IQE. To date, the Team has demonstrated ~ 100% internal quantum efficiency in a green PHOLED and is working to achieve the same with red and blue. As a result, it is reasonable to project that 100% IQE is attainable.

(b) Reduction in Drive Voltage to 3.0 Volts.

Currently, phosphorescent OLEDs have operating voltages of 5 – 8V, when illuminated at 500-1,000 cd/m^2. The actual voltage drop across the emission layer itself is usually 2 to 3V, depending on the emission wavelength. The remaining voltage is dropped mainly across the ETL, HTL and at the heterojunction interfaces. Current transport in low mobility organic films is space-charge limited, and high electric fields are required to inject the necessary charge to generate the desired photon flux. Band mis-alignments at the heterojunction interfaces also result in voltage loss.

By combining these factors, the operating voltage can be reduced to 3.0V. We have demonstrated white PHOLEDs with a total power efficiency of 29 lm/W at 100 nits in the forward viewing direction at 4.0V, and a total power efficiency of 17 lm/W at ,1000 nits in the forward viewing direction at 4.8V

(c) Outcoupling Efficiency from 20% to 40%

To a first approximation the outcoupling efficiency, i.e. the fraction of light emitted by the device, χ is given by [14].

$$\chi = 1 - (1 - (1/n_i^2))^{1/2} \qquad (4)$$

where n_i is the refractive index of the emissive layer. For typical materials used in our devices, $n_i = 1.7$, resulting in an outcoupling efficiency of 19%. Most of the remaining light is waveguided in the substrate and organic layers.

Hence, currently, the most significant limitation to the efficiency of OLEDs, and one that is of particular importance in considering their use in lighting applications, is total internal reflection of emitting light in the glass substrate. In this case, without light extraction enhancement, $\eta_{ext} = 20\%$ presents a fundamental limit for devices with 100% internal efficiency.

In our SBIR Phase 1 entitled "Novel Light Extraction Enhancements for OLED Lighting", we are integrating a novel hemispherical lens array to an OLED glass substrate with the expectation of achieving quantum efficiencies above 25%. Results show that our microlens arrays currently provide an average 30% improvement for all viewing angles in the outcoupling efficiency over devices without microlenses. This means that the outcoupling efficiency of devices with mircolens arrays is 26% versus devices without lenses having an outcoupling efficiency of 20%.

With the advances discussed above, performance from the current level of 15-30 lm/W has the potential to achieve the desired > 100 lm/W as shown in Table I. We believe that this efficiency target can be accomplished before 2025.

Parameter	Current Status	Practical Limit
Light extraction	~ 40%	60%, with outcoupling enhancement of waveguided modes
Brightness (cd/m^2)	800	Trade-off with lifetime
Lifetime (hrs.)	20,000 (red, green)*	50,000
Red luminance eff (cd/A)	60	72
Green luminance eff (cd/A)	140	210
Blue luminance eff (cd/A)	12	72
Device Voltage	9	3.5
Lifetime for 800 cd/m2	5,000	50,000
Power efficiency (lm/W)	**30**	**150**

Table I: Pathway for meeting commercial lighting efficiency targets based on best UDC red and green data and assuming a phosphorescent saturated blue at CIE (0.15, 0.15). A saturated blue is desired to achieve (0.33, 0.33), and CRI >80. Research on long operational stability of saturated blue PHOLEDs, for cool whites, is progressing rapidly, but less saturated blue PHOLEDs with more operational stability may offer a solution for warm whites with correlated color temperatures below 4,000 K.

Conclusions and Recommendations for Future Work.

The TOLED of the final deliverable had the following performance characteristics: At 20 lm flux output, the power efficiency is ~9 lm/W, and 10 lm/W at 1.5 lm. At ~10 lm output, the emission from the front and back surfaces of the device is 1050 cd/m^2 and 200 cd/m^2, respectively. The CIE coordinates were (0.39, 0.39), the CRI was 70, and the correlated color temperature is 4400 K, which corresponds to a warm white color akin to an incandescent lamp color. The TOLED light source has a projected lifetime of **>3,000 hrs at 600 cd/m^2** with only a minor chromaticity shift over the operational lifetime of the system. The 1931 CIE chromaticity shift with aging is <= 0.02 for both the x and y CIE coordinates, and to yield the large area transparent PHOLED, we employed a new transparent cathode consisting of LiF/Al/Ag. In summary:

- Successfully demonstrated the first integrated window technology that combines an electrochromic mirror and a light source.
- Developed electronic driver system to operate smart window.
- Worked closely with DOE to keep program focus.
- Initiated new relationship with Rockwell Scientific to build smart window.\
- Completed program on time.

OLED efficacies have been increasing exponentially over the last ten years, so these devices hold the potential to satisfy the energy demands in future lighting applications. The team of Universal Display, the University of Southern California, and Princeton University has tremendous expertise, recognition, and respect in the field of OLEDs, and our phosphorescent dopants are key elements in the ability of OLEDs to meet DOE goals in the next ten years.

There are three major areas that require attention to continue the advancement of OLEDs for general illumination: PHOLED efficiency and stability, lower operating voltages, and higher outcoupling efficiency. Large scale commercialization also requires low cost production and packaging technologies.

Blue PHOLEDs are currently the weakest link in terms of stability. This issue is being addressed by our team through the development of new materials, device architectures and processing conditions. We strongly believe that we will have this problem mitigated within the next few years.

Interestingly, we have realized that, given our current inventory of materials and devices, increases in red PHOLEDs efficacies have greater impact on overall white OLEDs that emit with a CIE similar to that an incandescent lamp. We have strived to engineer PHOLED lighting panels that will eventually replace incandescent lamps, and red emission accounts for over 55% of the total optical power output of incandescent lamps, so it more advantageous, presently, to increase the efficacy of red PHOLEDs. To improve our red PHOLED performance, we need to lower the operating voltages of our devices from 6-8 V to 2-3 V, and this effort will require new materials, device structures, and processing techniques.

Finally, the theoretical outcoupling efficiency of devices limits OLEDs to ~40% of their maximum total power efficacy. To meet the DOE's goal of a 50% energy efficient device, this challenge will need to be addressed more fully. The OLED industry needs to improve the outcoupling efficiency by a factor of 1.5 or find ways to more effectively use the generated light by employing fixtures that direct light into work areas. We are sure that with more time and resources that this challenge will be surmounted.

PHOLEDs are undoubtedly leading the march towards organic SSL products due to their demonstrated high quantum efficiency, and TOLEDs represent a unique opportunity to create smart windows for general illumination purposes.

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