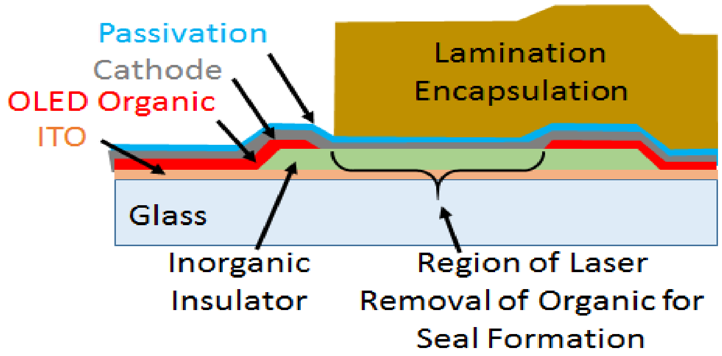
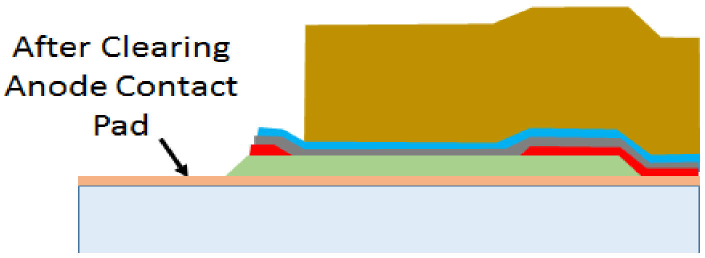
Mask-Free OLED Fabrication Process for Non-Tunable and Tunable White OLEDs





OLEDWorks LLC
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Project Summary

Timeline:

Start date: 10/1/2017

Planned end date: 9/30/2019

Key Milestones

1. Mask-free amber OLEDs demonstrated with performance comparable to control OLEDs; 9/30/2018
2. Mask-free white tunable OLEDs demonstrated; 9/30/2019

Budget:

Total Project $ to Date:

- DOE: $182,194
- Cost Share: $45,550

Total Project $:

- DOE: $1,490,826
- Cost Share: $372,707

Key Partners:

Keyence Corporation of America
Kurt J. Lesker
Thin Film Devices

Project Outcome:

OLEDWorks will develop and demonstrate a novel OLED manufacturing process that eliminates the use of shadowmasks during the vacuum thermal evaporation (VTE) process. This technology has the potential to reduce the cost of OLED lighting toward the DOE goal of < $100/m^2 by 2025 by lowering depreciation and operational costs, increasing yield, and enabling a path to lower cost roll-to-roll manufacturing. It will also enable lower cost manufacturing of tunable white OLED lighting panels.

Team

OLEDWorks LLC

- Equipment integration
- Process and technology development
- > 500 years combined OLED experience within company
- Prior DOE-sponsored projects successfully developed advanced vapor deposition sources and high performance OLED panel technology

Kurt J. Lesker

- Vacuum equipment fabrication vendor for R&D and production coaters

Keyence Corporation of America

- Laser system provider
- Assist in pre-selection and testing of lasers

Thin Film Devices Inc.

- Substrate fabrication vendor
- Assist in substrate material selection

Challenge

Lighting accounts for almost 20% of total U.S. electricity use. Solid-state lighting (SSL) has the potential to save 5.1 quadrillion BTUs of energy annually by 2035, including contributions from complementary LED and OLED lighting technologies. To meet these long term goals, SSL must continue to improve performance and reduce costs. While LEDs have already achieved impressive cost reduction, the less mature OLED technology still suffers from high initial costs and slow adoption typical of new technologies. Additionally, OLEDs have not entered the fast-growing tunable white lighting segment yet due to high cost and lack of commercially viable technology.

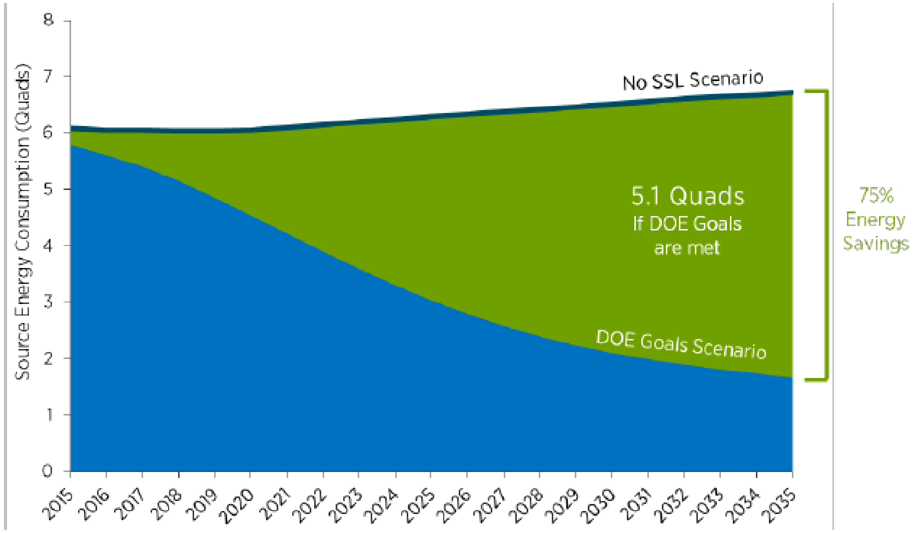
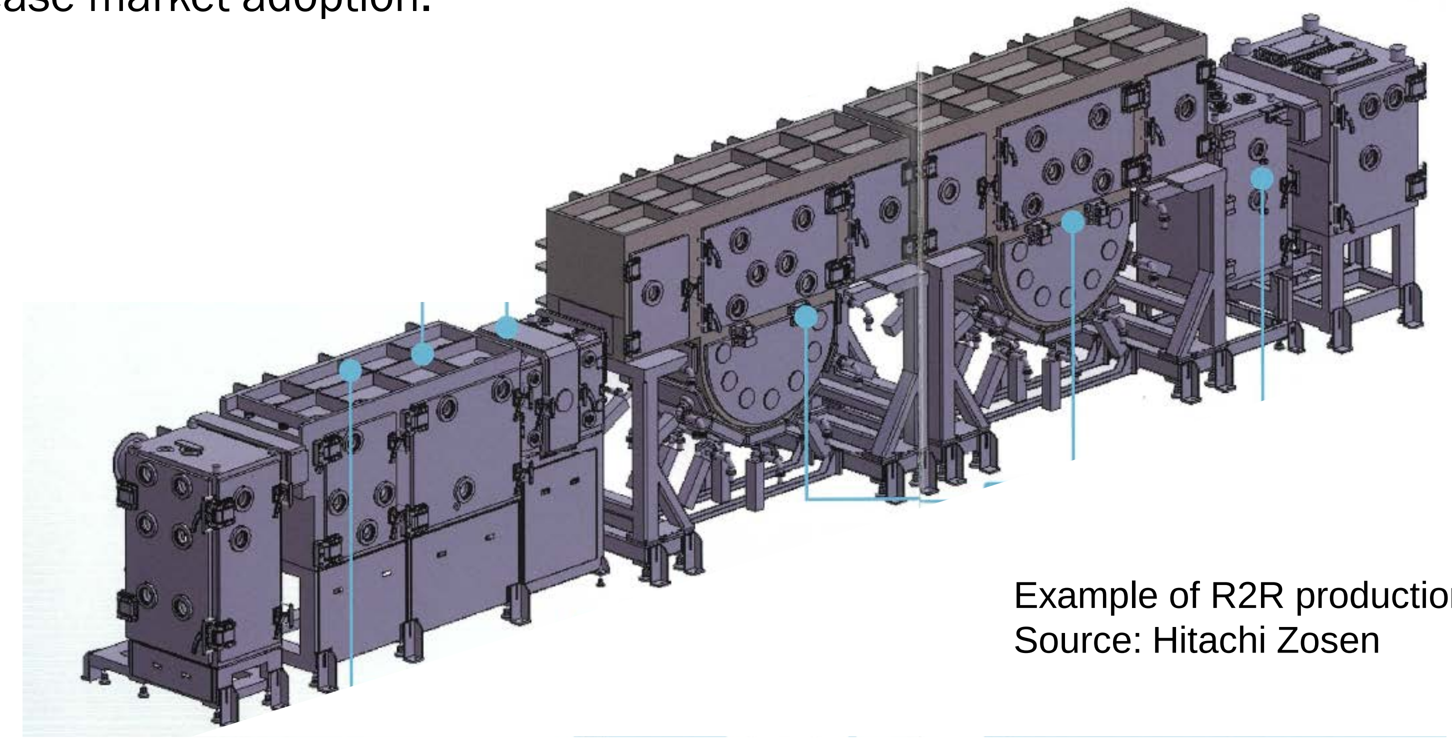


Figure E.1 DOE SSL Program Goal Scenario Energy Savings Forecast for the U.S. from 2015 to 2035

Source: DOE SSL Program, "Energy Savings Forecast of Solid-State Lighting in General Illumination Applications," September 2016 [1]

Challenge

The current sheet-to-sheet (S2S) production method for OLEDs is very expensive to scale. Continuous roll-to-roll (R2R) processes have potential to greatly reduce OLED manufacturing costs, but the use of shadowmasks is impractical in such systems. A mask-free process would not only remove a major barrier to R2R, but would also reduce equipment depreciation and operational costs associated with the current S2S method. A low cost method for producing tunable white OLEDs would also help to increase market adoption.



Example of R2R production line
Source: Hitachi Zosen

Approach

All OLED displays and lighting devices are currently manufactured using at least 2 shadowmasks to pattern the organic and metal layers. This requires expensive in-vacuum robots and mechanisms to handle and change masks within the vacuum system. The operating costs associated with purchasing new mask sets for every new design and regular cleaning of the masks can also be quite high.

Our solution: OLED fabrication process that eliminates the use of shadowmasks. This includes modification of the substrate, laser processing within the vacuum deposition system, and changes to the post-encapsulation processing.

- Allows for blanket deposition of all layers
- Opens the possibility for future cost reduction using R2R processing
- Demonstrated on both research and production scale equipment

Other possible solution: Direct patterning of the OLED by inkjet printing. Drawbacks to this approach include:

- Performance of solution-coated OLEDs is still inferior to vacuum-coated OLEDs
- Upper layers in stack (ETL and Cathode) may still require masking
- Difficult to make stacked OLEDs required for high performance OLED lighting

Approach

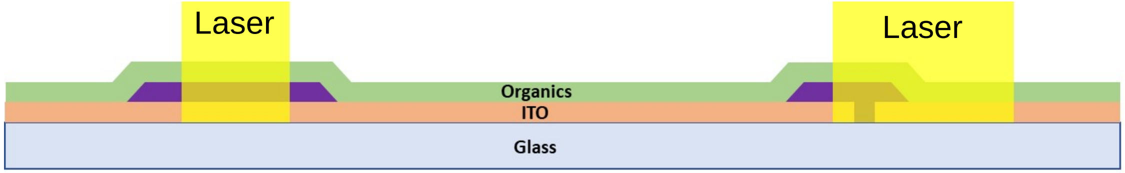
Year 1 (Budget Period 1):

- Pre-selection of laser technology
- Modification of small-scale R&D vacuum coater and integration of laser system
- Development of substrate technology
- Development of laser removal process in R&D coater on 4”x4” substrate

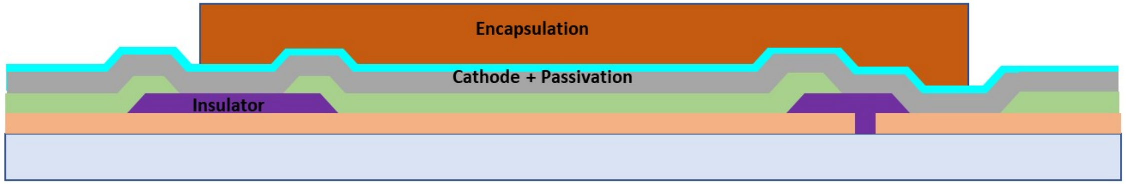
Keyence 9.3um wide area CO_2 laser

R&D OLED vacuum coater

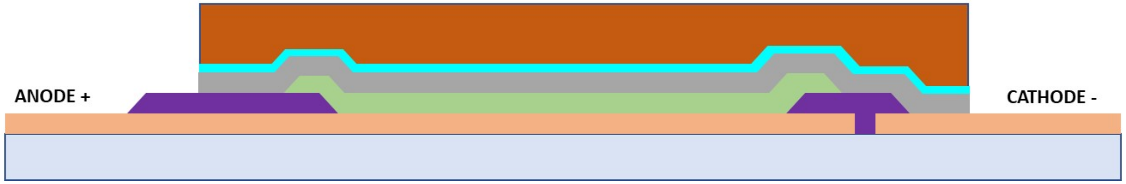
1. OLED organics blanket deposited on substrate with patterned ITO and Insulator
2. Selected areas of organics removed by laser ablation/re-sublimation



3. Blanket deposition of cathode and passivation layers, followed by encapsulation



4. Post-encapsulation process to expose electrical contacts

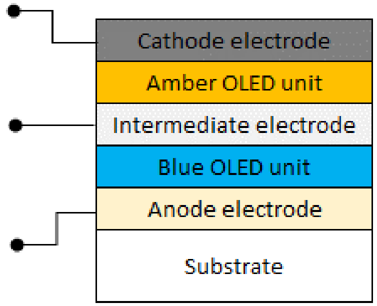


Approach

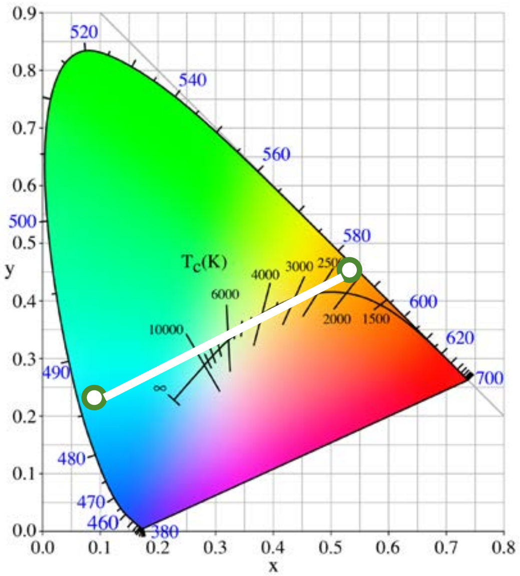
Year 2 (Budget Period 2):

- Modification of large-scale production OLED coater and integration of laser system (moved from R&D)
- Development of laser removal process in production coater over 300mmx300mm wide area
- Development of white tunable OLED technology and multi-step laser removal process

Stacked OLED with 3 independently addressable electrodes



Simple white tuning achieved by varying ratio of blue to amber emission

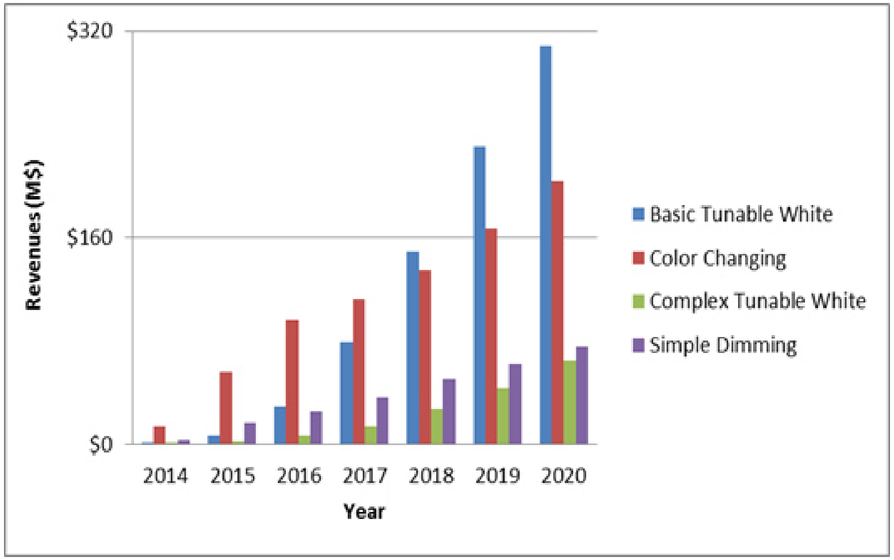


Impact

DOE SSL program goal for cost of OLED lighting is $100/m^2 by 2025. This requires scaling of manufacturing capacity and higher throughput. Demonstration of a mask-free process would help with the decision to invest in larger S2S manufacturing lines by reducing initial investment and lowering operational costs:

- Estimated 15-20% capital cost savings on S2S equipment due to elimination of mask handling systems (8-10% reduction in COGS)
- Eliminate operational costs for mask purchase and cleaning (5% reduction in COGS)
- Future cost savings for R2R processing, estimated by industry experts to reduce cost by up to 30% due to much higher throughput

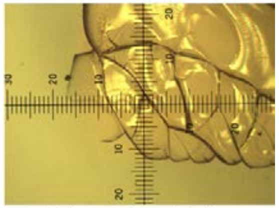
Tunable white lighting is predicted to grow rapidly with 90% CAGR over the next few years. There is a substantial market growth opportunity if OLEDs can enter the tunable white lighting segment.



Source: Strategies Unlimited

Progress

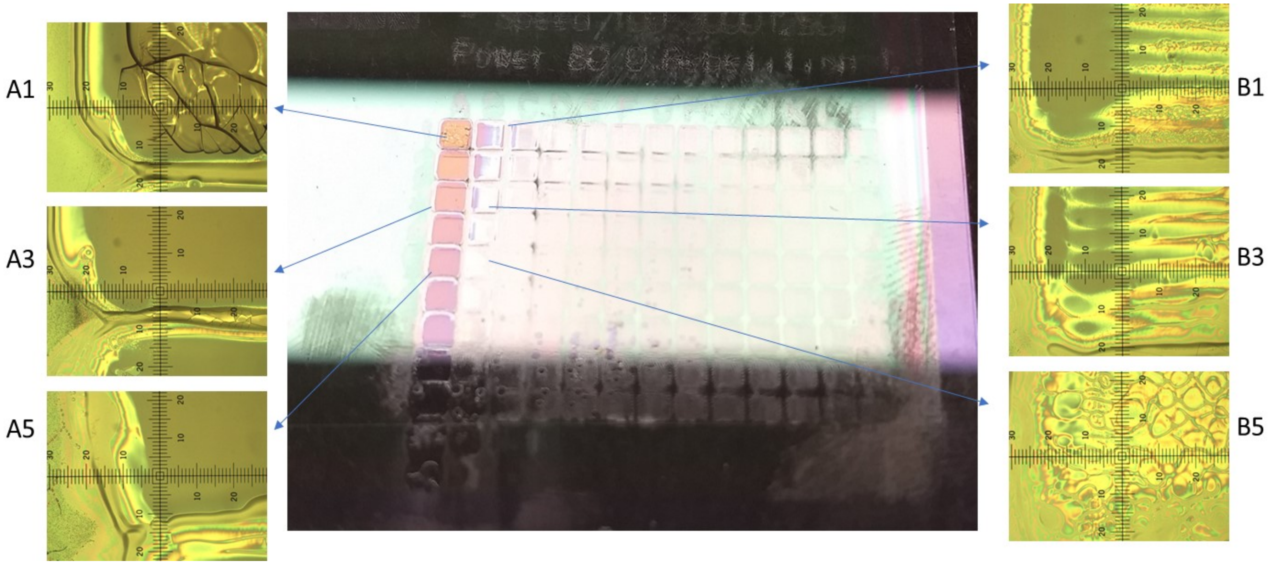
- Project is in early stages, midway through first budget period
- Completed first 2 milestones on schedule and within budget
  - ➢ Demonstrated feasibility of high speed laser removal of organic material on test samples without damage to underlying substrate


After solvent strip

Highest power, slowest speed: Organics removed but insulator damaged

Inadequate removal

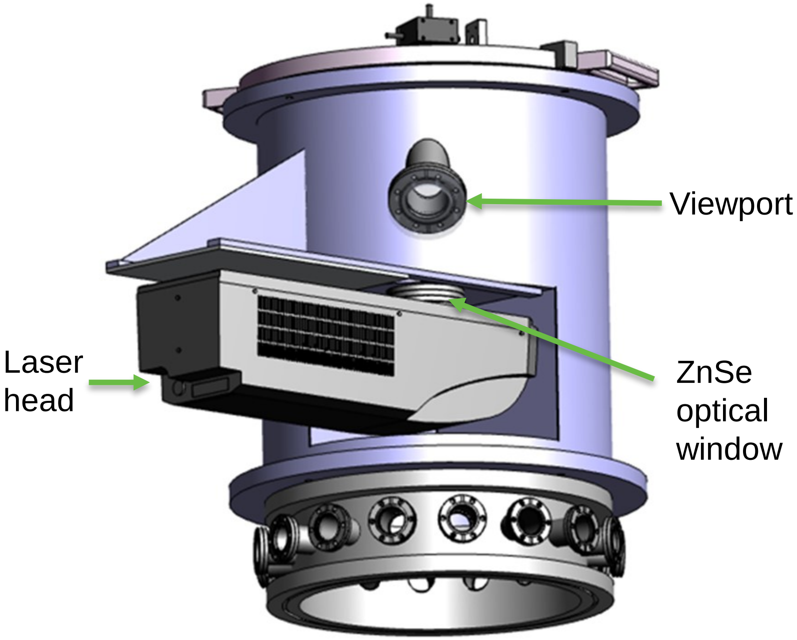
Best process conditions



Progress

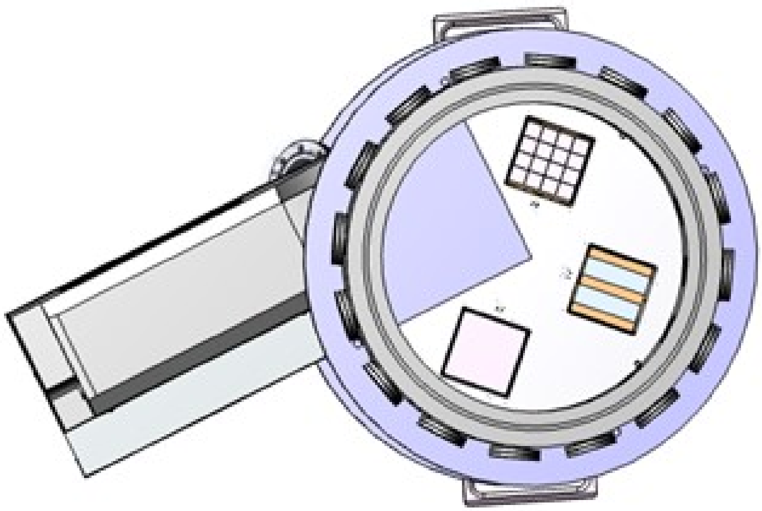
- Research coater modifications and laser system integration completed on schedule, now starting process development work in coater

Side view of vacuum chamber with laser head protusion into chamber



- When laser is not in use, shutters will protect optical window and viewport from organic material build-up

Bottom view of vacuum chamber



- Laser occupies one quadrant of chamber
- Substrate parked over laser for processing after blanket deposition of organic layers

Stakeholder Engagement

- Worked with laser system vendor prior to and during early stages of project to assess laser equipment and process feasibility, including lab demonstrations and on-site visits
- Engaged substrate suppliers early on to determine appropriate materials and ensure timely substrate supply to avoid project delays
- Discussions with current and potential customers indicate strong support for lower cost OLED lighting panels and color tunability feature
- OLEDWorks' investors committed to advancing state-of-the-art and providing necessary cost share to be successful
- DOE SSL program management very supportive of efforts to continue cost reduction and advancement of OLED SSL technology

Remaining Project Work

Remainder of Budget Period 1:

- Develop high-speed laser removal process in R&D coater
- Demonstrate amber OLEDs using mask-free laser removal process having performance within 90% compared to control OLEDs made with masks
- Demonstrate initial feasibility of tunable amber OLED (red-to-green) using multi-step laser removal process. White tunable not possible due to limited number of organic materials available on R&D coater. Material development for transparent intermediate electrode.
- Complete design work for installation of laser system on production coater (start 4 months prior to BP2)

Budget Period 2:

- Install laser system on production coater
- Develop and optimize large area laser removal process
- Demonstrate performance of mask-free amber and white OLEDs
- Demonstrate tunable white OLED panel with tunability from 2700K to 5000K

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: Total budget of $1,863,533 with DOE share of $1,490,826 (80%) and cost share of $372,707 (20%).
Variances: No variances to date.
Cost to Date: As of 3/31/18, approximately 12.2% of the project funds have been spent ($227,744 out of $1,863,533).
Additional Funding: None.

Budget History					
10/1/17 – FY 2017 (past)		FY 2018 (current)		FY 2019 – 9/30/19 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$76,360	$19,090	$105,834	$26,460	$1,308,632	$327,157

Project Plan and Schedule

- 2 year project
- On schedule to date
- Go/no-go decision point at end of year 1 (Q4 FY2018)

Project Schedule												
Project Start: 10/1/2017		Completed Work										
Projected End: 9/30/2019		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned)										
	◆	Milestone/Deliverable (Actual)										
	FY2018				FY2019				FY2020			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Q1 Milestone: Laser Removal Process Demonstrated	◆											
Q2 Milestone: Laser R&D System Operational		◆										
Current/Future Work												
Q3 Milestone: Mask-Free Amber OLEDs Demonstrated			◆									
Q4 Milestone: Tunable Amber OLED Feasibility				◆								
Q1 Milestone: Laser Production System Operational					◆							
Q2 Milestone: Mask-Free Amber OLEDs Demonstrated						◆						
Q3 Milestone: Mask-Free White OLEDs Demonstrated							◆					
Q4 Milestone: Tunable White OLEDs Demonstrated								◆				