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Lighting R&D Program:

Panel Structures and Manufacturing R&D Meeting

February 2021

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DOE Lighting R&D Program, "Panel Structures and Manufacturing R&D Meeting", February 2021.

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Comments

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1 Introduction

On October 29, 2020, experts in organic and quantum dot light emitting devices gathered at the invitation of the Department of Energy (DOE) Lighting Research and Development (R&D) Program to help identify critical R&D topic areas in the fields of panel structures and manufacturing of diffuse light sources. This year, for the first time, the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing the state of understanding of the structures that are needed to feed current, extract light, and protect the fragile organic light emitting diode (OLED) or electroluminescent quantum dot (QDEL) materials in luminaires to identify gaps and suggest new R&D to advance understanding. The challenges associated with the layers in which OLED molecules and quantum dots convert energy from electrical current into light were discussed in a previous R&D meeting held on October 8th (see *Lighting R&D Program: Diffuse Light Sources R&D Meeting*). The presentations were followed by a general discussion of the R&D challenges and barriers to implementation. Finally, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop to be held February 1-4, 2021.

The meeting format provided an opportunity for OLED and materials experts in the field to exchange ideas and explore collaborative research concepts. Participants included invited experts in science and engineering drawn from academia and industry.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks within the existing task structure. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A of the report.

1.1 Key Conclusions

The meeting format encouraged each of the attendees to participate and present their perspectives on critical R&D challenges. The discussions ranged from device design and material selection to manufacturing techniques, with overall goals of reducing cost and enhancing performance. The major conclusions can be divided into three areas, as described in more detail in Section 2:

- Integrated substrates – better structures are needed as a foundation onto which the organics are deposited, providing protection from environmental damage, optimal light extraction, and uniform distribution of current across the panel.
- Increased throughput and cost reduction in the deposition of the light emitting layers – faster deposition of the organic layers is needed and could be facilitated by roll-to-roll (R2R) processing.
- Encapsulation and panel formation – sealing, separating and integrating panels into luminaires offer major opportunities for cost reduction.

2 Critical R&D Topic Areas

2.1 Integrated Substrates

The structures onto which the light emitting layers are deposited are critical for the performance of OLED or QDEL luminaires. In addition to providing support and protection for the fragile emitting materials, the integrated substrate (IS) must supply electrical current uniformly over the panel and enable as much light as possible to pass from the emission layers (which have high refractive index) to air. Since the materials and manufacturing processes are very different from those needed to form the emission layers, OLED panel makers often prefer to purchase the IS from an external supplier. However, the current dependency on suppliers from Asia slows down panel production, and the development of U.S. suppliers would be very helpful.

2.1.1 Basic Substrate

The current substrate of choice is display glass with thickness between 0.1 and 0.9 mm. This provides excellent protection against the ingress of water and oxygen and allows some flexibility with bending about a single axis with radius of curvature down to 10 cm. The use of glass places no constraint on the temperature at which deposition processes can be conducted. The major disadvantage is the fragility of ultra-thin glass.

Plastic substrates, such as polyethylene terephthalate (PET) and polycarbonate (PC), are being explored in many research projects. The major challenges are in the addition of barrier layers to exclude H_2O and O_2 and the limited temperature range that can be tolerated in the deposition of transparent conductors and organic materials. Whitney Gaynor described the integrated substrates Sinovia made in partnership with Vitriflex that comprise inorganic barriers with water ingress rates below 10^{-5} g/m^2/day and silver nanowire anodes with sheet resistance less than 10 Ω/square.

2.1.2 Light Extraction Layers

In the absence of structures to enhance light extraction, only 20-30% of the photons created by the OLED or QD materials can escape into air. The major way to extract more light is to introduce light outcoupling structures between the substrate and anode. There are two approaches to the design of such structures. One is to add planar layers between the substrate and anode consisting of light scattering particles in host matrix with a high index of refraction (to correspond with the refractive index of the OLED stack). Selina Monickam reported that this method has been used by Pixelligent to increase extraction efficiency from 22% to 50%, enabling the construction of an OLED with efficacy of ~125 lm/W. This can be achieved without the use of an external extraction layer.

The alternative approach is to break the planar symmetry by creating corrugated interfaces with substantial difference in refractive index. The corrugations can extend through the device, or a planarization layer can be included below the organic layers. Research is still needed to understand the optics and optimize this approach. Manufacturability is still an issue, but several participants are confident that the structures can be formed in a roll-to-roll line.

It is clear that the optimal form of light extraction structures depends on the nature of the organic stack. The stacks can be designed to facilitate light extraction, for example, through reduction of the refractive index, orientation of the emitting molecules, cavity effects, and placement of the emitting material for control of the excitation of surface plasmons.

2.1.3 Transparent Conductors

Despite many years of R&D on alternative transparent conductors, indium tin oxide (ITO) remains the material of choice for both lighting and display applications. It seems to be adequate for lighting panels up to 200 mm in dimension. It could also be used on its own in larger panels; but for adequate light uniformity across the panel, the thickness would need to be increased, leading to greater light absorption. An attractive alternative is to use nanowire or metal meshes with a field conductor, possibly of thin ITO, for maximizing the emissive area and increasing uniformity of emission across the panel.

2.2 Manufacturing Throughput

Increased throughput is the key to cost reduction and can best be achieved by reducing processing time, along with modest increases in substrate size or web width, perhaps up to 1.5 m in dimension. Two of the rate-limiting steps are organic deposition and encapsulation. The use of organic vapor phase deposition (OVPD) may enable higher deposition rates for organic materials at modest chamber temperature. The best way to form encapsulation layers is unclear. Inorganic barrier layers could possibly be formed by atomic layer deposition (ALD) or physical vapor deposition (PVD) rather than the plasma-enhanced chemical vapor deposition (PE-CVD) that is used for OLED displays.

Roll-to-roll processing is being explored as a way to increase throughput, either in the manufacture of integrated substrates or in the whole OLED production. Two critical issues are thermal management and defect prevention as the web passes between processing steps. Very high levels of equipment reliability and process yield are needed since the whole line is interrupted if one tool has to be stopped to attend to a malfunction.

Although market demand and the availability of capital are essential factors in manufacturing scale-up, R&D is needed in many aspects to increase throughput and yield and reduce costs. These challenges will be especially important for OLED lighting in the next decade.

2.3 Back-End Processes

The processes that are necessary after the substrate is cut into separate panels contribute a substantial fraction of the cost of OLED panels and luminaires, especially with respect to the bill of materials and labor. OLEDWorks estimates these costs can account for as much as one-third of the panel cost. Although most of the needed improvements will come from the development of manufacturing practices, opportunities for R&D should be sought, for example, in the replacement of the PCB boards around the panel perimeter. New designs of low-power, multi-channel drivers are critically needed, as discussed in a previous R&D meeting held on October 28th (see Lighting R&D Program: *Luminaire Integration and Market Expectations R&D Meeting).*

2.4 Alternative Approaches

While OLEDs have been the most promising source for flexible diffuse lighting panels, other possibilities are emerging. Electroluminescent quantum dots and perovskites could build on much of the infrastructure that has been developed for OLEDs and possibly offer the opportunity for simpler manufacturing. However, their performance is still inferior to that of OLEDs, both in efficacy and lifetime.

Although inorganic LEDs have been used as the light source in rigid LCD displays for many years, the production of flexible flat panel displays has relied almost entirely on OLEDs. The availability of efficient and reliable micro-LEDs may change this situation. The R&D that is now underway on the incorporation of micro-LEDs in display backlights may also provide opportunities in lighting.

Appendix A: Participant Presentations

Whitney Gaynor, President and CEO, Sinovia Technologies: Integrated Plastic Substrates for OLED Lighting

Whitney Gaynor, President and CEO of Sinovia Technologies, stated that substantial cost reduction will be needed if OLEDs are to capture a significant portion of the general lighting market. She described their DOE-sponsored project to fabricate a complete IS based on a polymer substrate using roll-to-roll manufacturing. If successful, this project will enable the production of luminaires with unique characteristics as well as lowered cost through the use of additive patterning. The process begins with rolls of PET with a moisture barrier deposited by Vitriflex using PVD. The water-vapor transmission rate (WVTR) is below 10^{-5} $g/m^2/day$. Gaynor suggested that this should be sufficient to support storage lifetimes of 50,000 hours and operating lifetimes of ~12,000 hours for OLED panels under standard conditions. The transparent conductor is formed using silver nanowires (Ag-NW) embedded in a polymer layer, producing a very smooth foundation onto which OLEDs can be deposited with low probability of shorting. The sheet resistance can be as low as 7 to 10 Ω/square with transparency between 82% and 85%. It had been hoped that scattering of light by the nanowires would help to enhance light extraction, but the amount of haze was relatively small at 6% to 8%. Nevertheless, the use of this IS led to an increase in external quantum efficiency of 21% to 28% in comparison to panels fabricated with ITO on glass. The potential for cost reduction comes primarily from the use of flexographic printing, which can be carried out at a very fast speed with spatial resolution down to 50µm. Gaynor suggests that patterning the panel shapes during deposition is better than laser removal of unwanted material around the edges, which leads to particle creation and may damage underlying layers. Sinovia believes that the whole manufacturing process can be carried out within DOE cost targets. More R&D is needed to improve yield, increase light extraction, and extend operating lifetime for OLEDs on this IS.

Franky So, Walter and Ida Freeman Distinguished Professor, North Carolina State University: Corrugated OLEDs

Franky So, Professor at North Carolina State University, described his project to explore the enhancement that can result from the use of corrugated glass substrates with low-index layers to increase the change of refractive index across non-planar interfaces. The corrugations have a height of 100nm and a pitch of ~350nm and persist through the many OLED layers up to the cathode. Angle-resolved EL spectra were analyzed to distinguish the role of the different modes. So stressed the role of cavity effects, which can be enhanced by the insertion of a low-index layer. The use of Teflon with a refractive index of 1.3 led to an EQE of 36%, which could be increased to 71% by the addition of a hemispherical lens to extract all the light that reaches the substrate. For multi-layer OLEDs with thicker stacks, the corrugation in the cathode is less pronounced, the cavity effects are suppressed, and more of the light remains trapped in the waveguide modes. So concluded by recommending further studies of light extraction in multi-stacked OLEDs.

Ruth Shinar, Adjunct Professor of Electrical and Computer Engineering, Iowa State University: Enhanced Light Outcoupling from OLEDs on Novel Low-Cost Patterned Plastic of Varying Periodicity

Ruth Shinar, Professor at Iowa State University, described work performed at Iowa State University in collaboration with Dennis Slafer of MicroContinuum. The goal is to design patterned plastic substrates to extract 70% of the light created in an OLED stack through the use of corrugated substrates. PET and PC substrates were used with corrugations of various pitch (400 nm – 8000 nm) and height (100 nm – 500 nm). Corrugations resulted in an EQE enhancement over planar substrates controls for both green and blue devices. Green device EQE of 56% was achieved (a 2.8x enhancement) and blue device EQE of 33% was demonstrated (a 2x enhancement). The team is now exploring the use of high index smoothening layers that allow a planar surface for depositing the OLED stack, yet retain the index contrast at the corrugated substrate/high index smoothening film interface that is needed to scatter the light out of the device. The team is also working to demonstrate this approach in white devices and improve the anode with use of an embedded copper mesh with a thin ITO field conductor. All of the light extraction and anode technology developed in this project is compatible with roll-to-roll manufacture.

Stephen Forrest, Peter A Franken Distinguished University Professor of Engineering, University of Michigan: Fabrication of SEMLAs in Thin Glass for Enhanced Outcoupling from Deep-Stack WOLEDs

Stephen Forrest, Professor at University of Michigan, talked about enhancing light extraction for thick white OLEDs which is more difficult than for single-layer monochrome emitters. The goals of their current project are to reach EQE of 40% for white and 70% for green stacked devices. To achieve this, they are developing glass substrates embedded with microlens arrays that increase outcoupling by extractive substrate and waveguide modes. The arrays are made by etching into the glass substrate and filling the holes with a high index polymer which is also deposited as a blanket layer beneath the ITO as a spacer layer. Preliminary results using index matched fluids to couple light out of the device show that the sub-electrode microlens array (SEMLA) structures that are placed on the inside of the substrate are successful in transferring most of the light into the substrate mode. Unfortunately, the addition of a microlens array has not been very effective in extracting the light from the substrate.

Selina Monickam, Product Development Manager, Pixelligent: High Refractive Index Materials for OLED Lighting

Selina Monickam, Product Development Manager at Pixelligent, described work being performed with support from the DOE SBIR program to demonstrate an OLED lighting panel with efficacy of 130 lm/W through enhanced light extraction. They have already achieved ~125 lm/W at 3000 cd/m^2 without an external extraction layer (EEL). The extraction efficiency was estimated to be 50%, up from 22% for a panel without extraction enhancement. One unexpected result was that the emission is not uniform but drops significantly at large angles. This may be problematic in some applications but could be advantageous in others, due to reduction in glare. Much work still needs to be done to build on this success, including:

- Improve extraction of blue light
- Understand angular dependence of emission
- Greater tolerance of high temperatures during processing
- Deposition of a transparent conductor that does not cause shorting
- Develop a method for large area uniform coating and UV curing

Stephen Forrest, Peter A Franken Distinguished University Professor of Engineering, University of Michigan: R2R Manufacturing of WOLED Lighting

Stephen Forrest, Professor at the University of Michigan, described a project being conducted in collaboration with Universal Display Corporation to study roll-to-roll manufacturing of OLEDs. By creating prototype devices in their lab scale R2R setup, the team hopes to understand limitations of R2R, test assumptions, and better estimate cost for scale-up. Their system combines organic vapor phase deposition (OVPD) which is used for the emitter layers, with the more traditional vacuum thermal evaporation (VTE) to deposit the other organic layers. The two processes operate at different pressures and so require separate deposition chambers. OVPD is of interest for R2R production as it has the advantage of higher throughput as the deposition rate can be controlled by both temperature and flow rate of the inert carrier gas. The researchers have found that OVPD can be carried out at rates up to 5nm/sec, but increased roll-off is observed at higher speeds. This roll-off is partially due to void formation.

With incorporation of an atomic layer deposition (ALD) chamber for encapsulation, the team will have a complete prototype R2R system for forming lab scale OLED devices. The program goal is to demonstrate R2R manufactured 4-stack OLED devices with high efficacy, long lifetime, and good color quality.

A cost model has been constructed for a system in which a web of width 1.5 m is fed at 9 m/min, giving an input capacity of over 6 million m^2 per year. The cost of the capital equipment might be around $250M but the throughput would be sufficiently large that depreciation costs are much less than the bill of materials. Their analysis suggests that the total cost could be around $100/m^2 (or $10/klm) in full production.

Dennis Slafer, President and CTO, MicroContinuum: Recent Insights and Future Research Priorities for Enhanced OLED Substrates

Dennis Slafer, President and CTO of MicroContinuum, described how MicroContinuum has focused on the use of R2R fabrication of an integrated substrate, which could be used in a complete R2R or roll-to-plate (R2P) OLED manufacturing line. Nanoimprint techniques can be used to create both ELE and ILE. Many forms of ILE can be printed. Options for the transparent conductor include a micromesh with 700nm lines of copper which blocks less than 1% of light. Barrier layers can be incorporated if plastic substrates are used. The only process that needs to be carried out in vacuum is sputtering of a 20-40nm layer of metal for the micromesh.

For R2P processing, structures that are created on plastic are transferred from donor film to glass. This can help to avoid the presence of polymer layers on the edge of the panels.

Jeffrey Spindler, OLEDWorks: OLED Panel Structures and Manufacturing

Jeffrey Spindler of OLEDWorks began by summarizing the performance of the Brite 3 panels from OLEDWorks. The goal for Brite 4 will be to increase efficacy to 120 lm/W at 3000 cd/m^2, by reducing voltage by around 5% and increasing extraction efficiency by about 30%. Greater improvement is anticipated in the bendable LumiCurve panel as an ILE is introduced. These panels are formed on 0.1mm Willow Glass from Corning as they have not yet found suppliers of plastic substrates with reliable moisture barriers.

OLEDWorks currently uses a six-stack organic structure with about 40 layers. The primary goal of the increased complexity is to reduce current density and increase operating lifetime. Some of these layers involve multiple components, which can be deposited together with good control over the relative densities. They hope to be able to reduce the number of stacks to 3 or 4 as efficacy is improved. After the stack is formed and cathode deposited, an Al foil with adhesive is added to protect the device and spread heat.

Spindler detailed the requirements for three important components:

- Light extraction structures
- Transparent conductors
- Thin film encapsulation

Spindler stressed that a lot of the manufacturing costs and problems are associated with the back-end processes after the substrate is separated into individual panels. 45% of the bill of materials comes from encapsulation and back end finishing, 30% from the integrated substrate, and only 25% from the organic materials.

Marc Baldo, Massachusetts Institute of Technology

Marc Baldo, Professor at Massachusetts Institute of Technology, stressed the importance of shortening the lifetime of excitons, especially in blue emitters. He suggested that the stability of phosphorescent blue emitters scales as the third power of the inverse of the exciton lifetime. His group has shown that the excitation of surface plasmons can speed up exciton decay. He believes that surface plasmons can play an important role in light extraction and in the stability of blue emitters and that these two effects should not be studied independently.

Ray Ma, Nanosys

Ray Ma, Senior Director at Nanosys, noted that most of the elements in a lighting panel based on electroluminescent quantum dots would be similar to those in OLEDs. Light extraction layers are still essential. The barrier requirements for plastic substrates and encapsulation may not be as severe, especially with respect to water. Oxygen must be kept away from the QDs. However, the intrinsic lifetime of QDs is still so short that this question cannot be answered with full confidence. Since quantum dots are deposited in solution, it is difficult to create multiple layers. One can mix all three colors in a single layer, but it may be better to separate the blue emitters from the red and green.

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