Problems and Opportunities in OLED Lighting Manufacturing

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Introduction to OLEDWorks

- OLEDWorks was founded in July 2010.
- Our goal is to manufacture cost-effective OLED lighting panels through innovation in product design, process design, and equipment design.
- Our team has over 200 years of combined OLED experience.
- We have a full production fab in Rochester NY.
- Our first product was introduced last year – an amber marker light for the health care market.
- We have will soon complete our commercialization of a competitive white OLED panel.
Two Key Challenges in OLED Lighting Panel Manufacturing

- **Reducing Variability** in performance of OLED lighting panels
  - Variability leads to lower yield of product within spec
  - Lower yield leads to higher panel costs

- **Improving Reliability** of OLED lighting panels
  - This is critical for successful market adoption – poor reliability contributed to slow adoption of CFLS’s.
  - We have heard complaints from luminaire makers of poor reliability of panels (across the industry).
Reducing Color Variability

• OLED panels are directly in view
• In OLED fixtures with multiple panels, it is not possible to combine off-color panels to generate on-spec light
  – Panel-to-panel color differences are easy to spot
  – It is possible to do this in LED lamps
  – OLED displays can correct by algorithm for white point variation.
  – OLED lights cannot do this
• Customers want very tight color consistency – important for replacement panels also.
• Color variability leads to lower yield.
  – Lower yield leads to higher costs
Major Reason Behind Panel-to-Panel Color Variability

- The efficiency of a color can be very sensitive to dopant concentrations within the layers.

- Some components like dopants can be in low concentrations in the layer – like 1-5%:
  - Control of these low concentration is difficult.
  - Measurement of these low deposition rates is problematic.
  - For example – 250 Å thick emissive layer with a dopant at 2%:
    - Equivalent of coating 5 Å thick.
    - This stretches the limit of what is possible be monitoring by QCM in multi-purpose design.

- Today, warm white OLED panels with long lifetime are usually triple stack – up to 20 layers.
  - The white color is sensitive to the relative amounts of light from each of the 3 stacks.
Challenge with Measurement of Dopant Deposition Rate by QCM

1 – Poor sensitivity at low rates

- Secondary components can vary from 1% to 50% of the material in the layer. Equipment is designed for this range.
- Rate on QCM can be 0.2 to 10 A/sec for 50:1.
- At the high end we have a QCM lifetime problem.
  - In research coater, there is no lifetime problem as QCM crystals are changed daily, so rate on QCM can be higher.
  - At 10A/sec on the QCM, the crystal will last < 1 day.
- At the bottom end of the range we have a sensitivity problem.
- QCM rate is determined by differentiation of frequency – inherent sensitivity limit ~0.05-0.1A/sec at sample rate of 1/sec
- We wish to control to +/-5% of target down to 0.2A/sec.
- Filtering (averaging) over many samples can improve apparent precision, but introduces lag in the measurement.
- This requires detuning the controllers to prevent instability.
- The detuning results in increased error from target rate.
Challenge with Measurement of Dopant Deposition Rate by QCM

2 – Noise on the QCM Signals

- QCM sensors are prone to noise.
- Some of noise comes from spring electrical contacts in multi-crystal sensors.
  - Achieving good electrical contact with spring contact in high vacuum system is problematic.
- The noise can be 10-100x the signal and is often associated with mode-hopping as the crystal ages.
- Noise can be removed by filters, but this introduces lag which requires the controllers to be detuned which increases the error from the target.

Conclusion
In order to reduce the color variability (to improve yield and reduce cost):
- We need better technology for measuring vapor deposition rate,
- Particularly for low rate components,
- With long lifetime between venting

Example of a multi crystal head
Improving Reliability of OLED Panels

• Early testing of OLED panels has shown problems with reliability – premature failure under use conditions (before LT70 is reached).
  – This failure is most commonly a short between anode and cathode.
  – The short causes the panel to stop lighting completely or light non-uniformly.
  – The industry wants larger panels, however these have higher occurrence rate of shorts.
• Experience from CFL’s shows that poor reliability can slow market acceptance by several years.
  – “Early consumer experience with fluorescent lamps and CFLs still defines attitudes towards CFLs, even though the technology has greatly improved since its introduction.” “You only get one chance to create a long-lasting, widespread reputation for your new lighting technology”

• There are no initial tests that can separate panels that will fail during service, from those that will not – ideas have included:
  – Current leakage measurements
  – Thermal imaging
  – Optical inspection (dark spots, bright spots,...)

• There are no well understood accelerated tests to establish reliability.
  – No accelerated test are established for shorting. Real-time testing takes years.
  – By comparison, we have accelerated testing for lifetime due to efficiency loss.

1CFLs and LEDs: Lessons Learned from New Lighting Technology Introductions, DOE Workshop, May 2014, PNNL
Improving Reliability of OLED Panels

• Most shorts occur at deviations in organic layer thickness
  – Deviations formed during panel fabrication
  – Due to particles or due to a roughness (e.g. scratch, spike) in the ITO

• The most common methods to prevent these include:
  – All operations in clean room – high expense
  – Stringent cleaning of glass – high expense
  – Use very high quality glass and ITO – high expense
  – Rigorous cleaning and PMs on OLED deposition equipment – shields, masks, etc.
  – Use solution coated Hole Injection Layers to planarize over the defects (e.g. Solvay, Nissan Chemical)
    • Requires patterning
  – This is not a guarantee – thin organic areas will have higher electric fields, higher current densities, and higher temperatures – all of which will accelerate the growth of the short. It is only a matter of time.
With HIL Smoothing Layer

• Higher field in thin areas lead to higher current density
• Higher current density leads to increased heating
• Increased heating leads to faster breakdown

Image of particle
Particles After HIL

Particles can form inside OLED coater

Invisible Particle

High Electric Field Breakdown

Normal Electric Field

Cathode

Organic

HIL Planarization

ITO

Sunic G5
Improving Reliability

- Particles and roughness come in all shapes and sizes
- Today to improve reliability, we rely on
  - Particle measurement in processes
  - Process improvement to reduce particles generation and occurrence
  - Long-term feedback from real-time testing of samples.

**Conclusion** – We need:
- Better particle measuring for process monitoring, glass monitoring
- Better understanding of “the life cycle of a short” from initial defect through growth to “killer short” – so we can predict which panels will fail in service, and which will not.
- Better technology for pushing shorting to beyond 50,000 hours and beyond. Nascent defect will always be present. Larger panels will be more likely to have defects.
Summary

• We have described two important problems for OLED lighting panel manufacturing:
  – Reducing color variability in OLED panels
    • Improves yield and lowers higher cost
  – Increasing reliability in OLED panels
    • Increases customer satisfaction and reduces warranty costs

• We recommend these as important areas for further manufacturing research and development.