Problems and Opportunities in OLED Lighting Manufacturing

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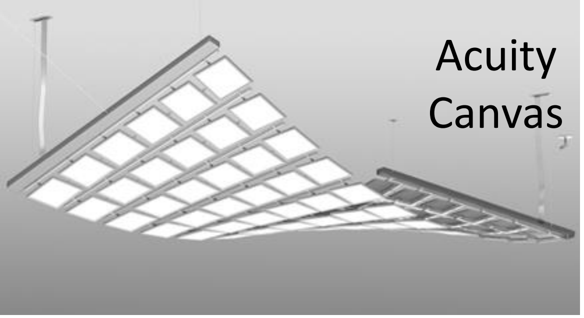
Introduction to OLEDWorks

- 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.

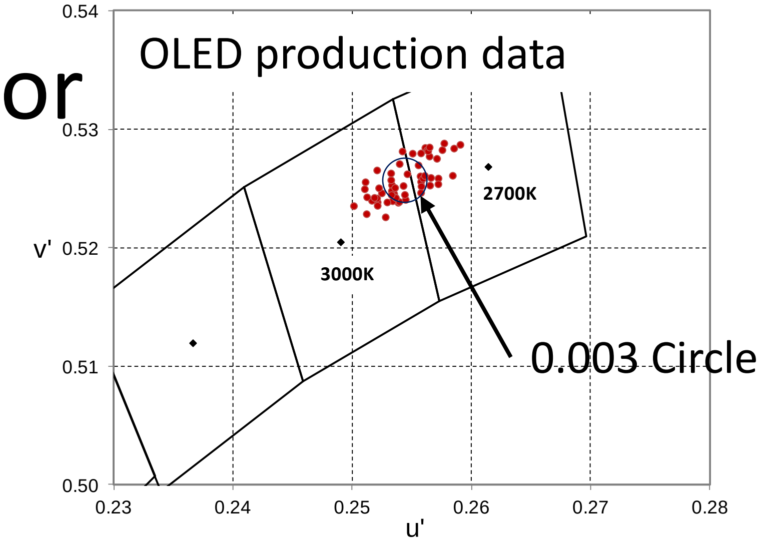
Two Key Challenges in OLED Lighting Panel Manufacturing

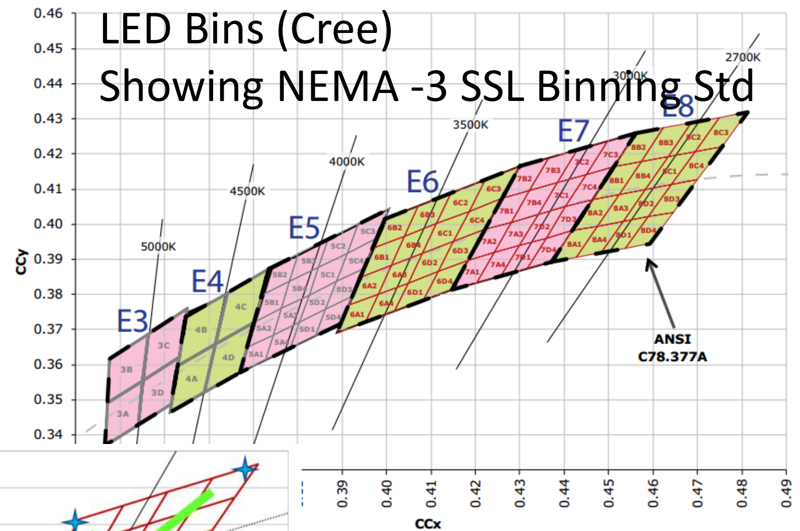
- Reducing Variability in performance of OLED lighting panels
  - Variability leads to lower yield of product within spec
  - Lower yield leads to higher panel costs
- Improving Reliability of OLED lighting panels
  - This is critical for successful market adoption – poor reliability contributed to slow adoption of CFLS's.
  - We have heard complaints from luminaire makers of poor reliability of panels (across the industry).

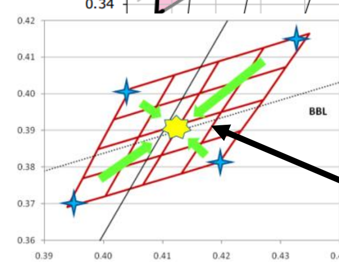


Reducing Color Variability

- 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 is easy to spot
  - It is possible to do this in LED lamps
  - OLED <u>displays</u> 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







Combining of off-color LED's

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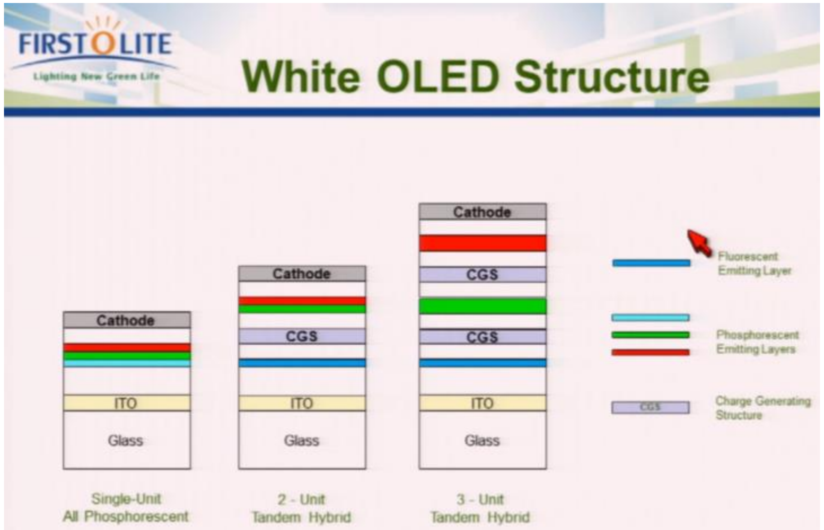
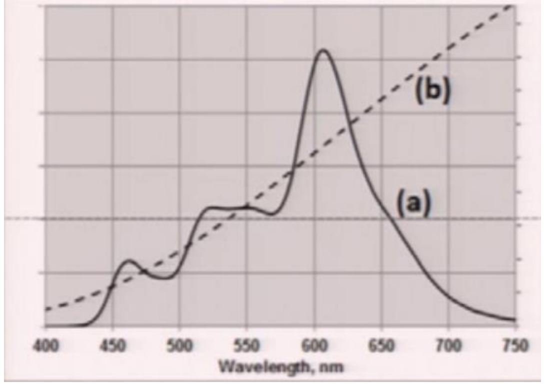
Major Reason Behind Panel-to-Panel Color Variability

- 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 A thick emissive layer with a dopant at 2%
    - Equivalent of coating 5A thick
    - This stretches the limit of what is possible be monitoring by QCM in muliti-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.





YS Tyan – SID 2014 Paper 47.2 Advantage of triple stack OLED for efficiency, lifetime, and CRI

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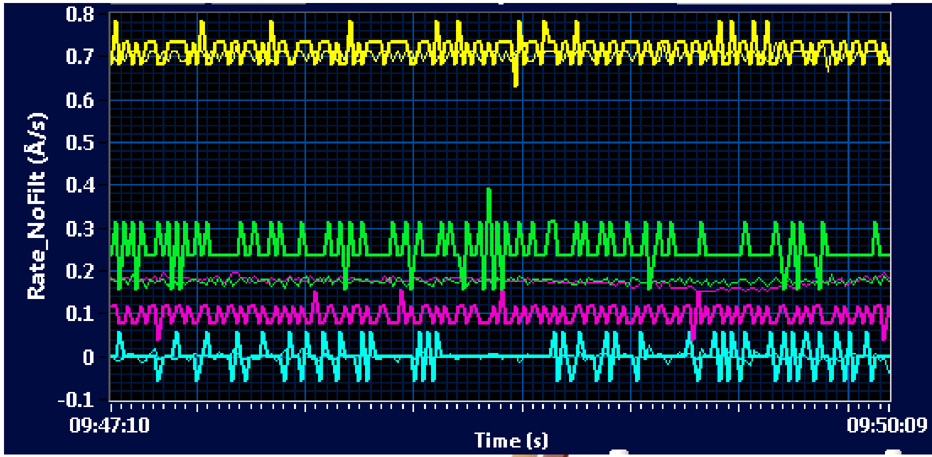
Challenge with Measurement of Dopant Deposition Rate by QCM

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.

Photo of production linear sources
“Applying OLEDs in a Manufacturing Process”, Kai Gilge, Ansgar Werner, and Sven Murano, SID Info Display, Jan 30, 2014



Challenge with Measurement of Dopant Deposition Rate by QCM
2 – Noise on the QCM Signals

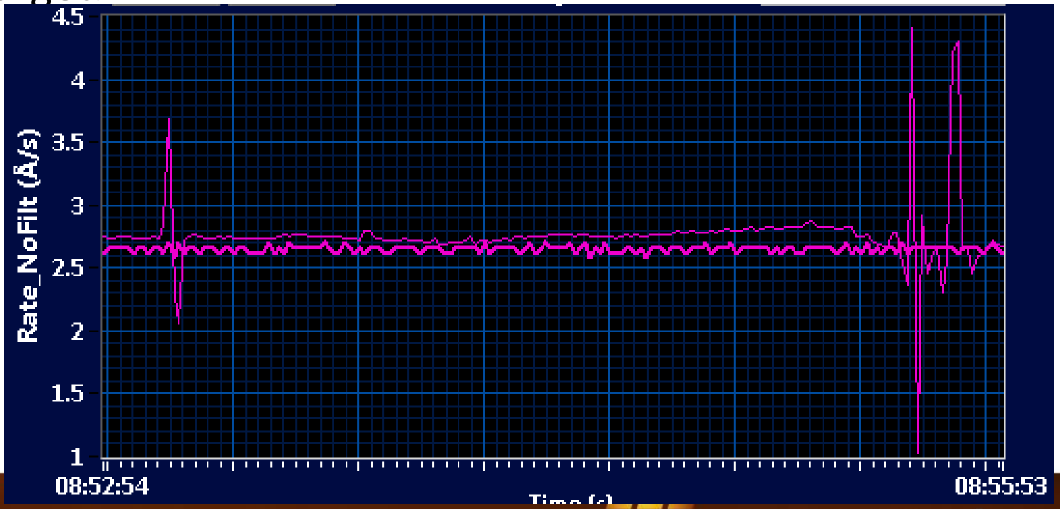
- QCM sensors are prone to noise.
- Some of noise comes from spring electrical contacts in mulit-crystal sensors.
  - Achieving good electrical contact with spring contact in high vacuum system is problematic.
- The noise can be 10-100x the signal and is often associated with mode-hopping as the crystal 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.

Example of a multi crystal head

<u>Conclusion</u>

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



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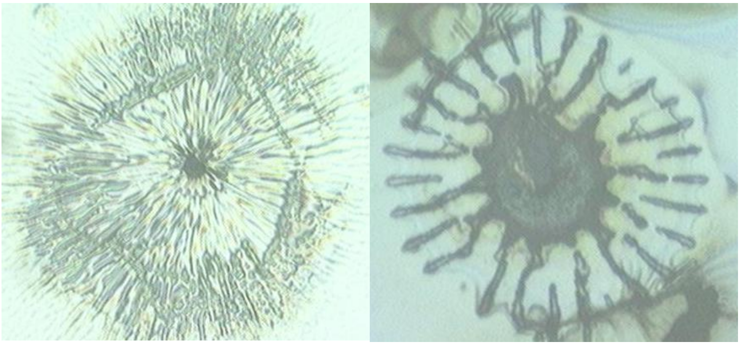
Improving Reliability of OLED Panels

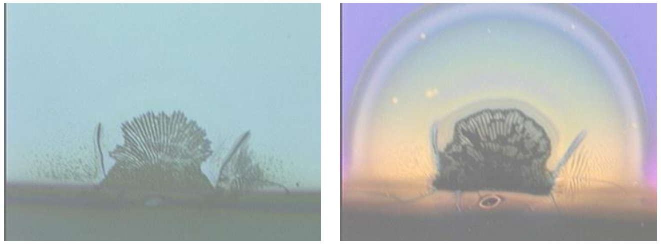
- Early testing of OLED panels has shown problems with reliability – premature failure under use conditions (before LT70 is reached).
  - This failure is most commonly a short between anode and cathode.
  - The short causes the panel to stop lighting completely or light non-uniformly.
  - The industry 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"[1]
- 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.

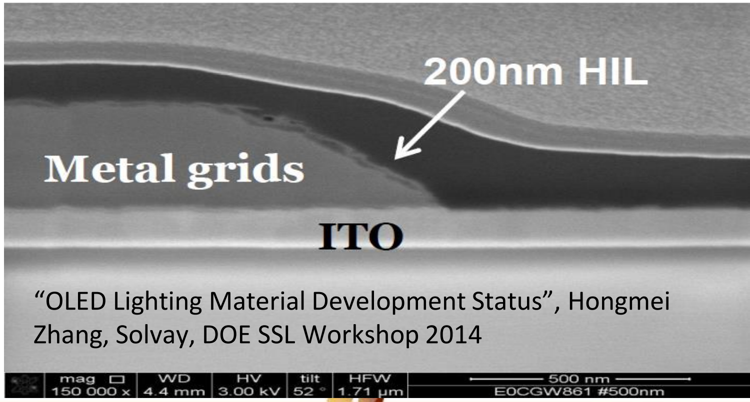
[1]CFLs and LEDs: Lessons Learned from New Lighting Technology Introductions, DOE Workshop, May 2014, PNNL

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.







"OLED Lighting Material Development Status", Hongmei Zhang, Solvay, DOE SSL Workshop 2014

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

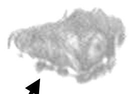
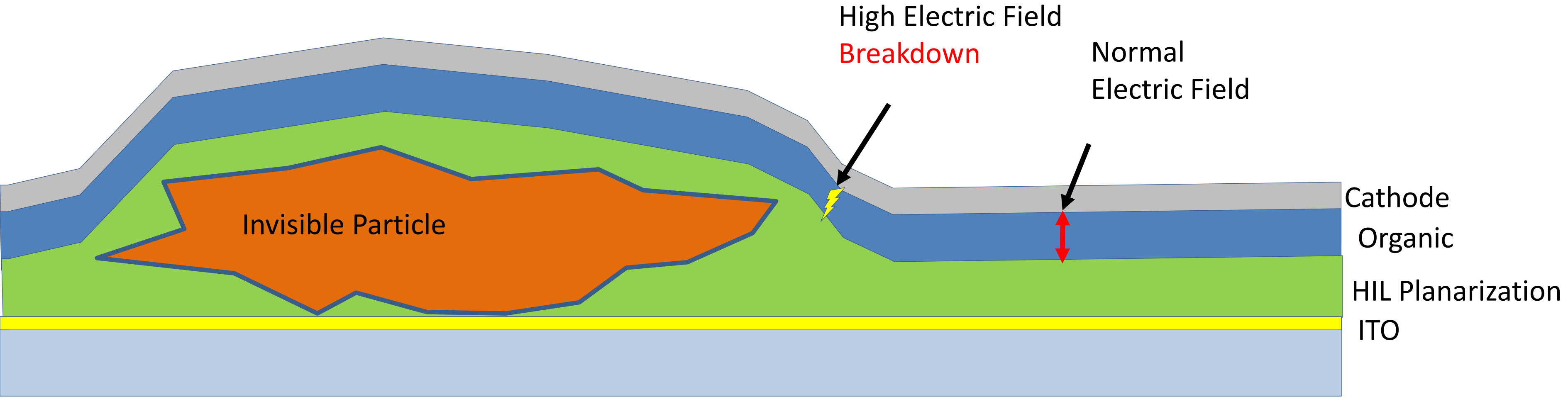
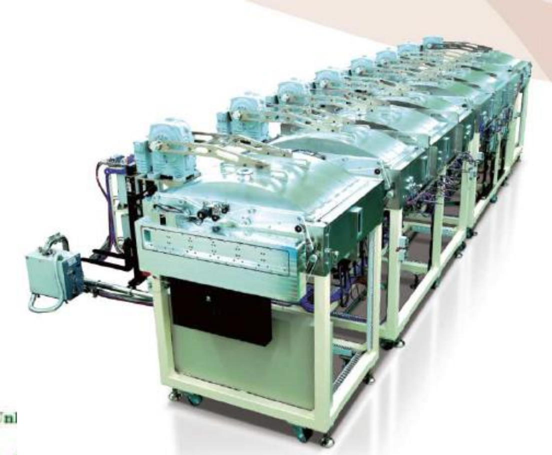


Image of particle

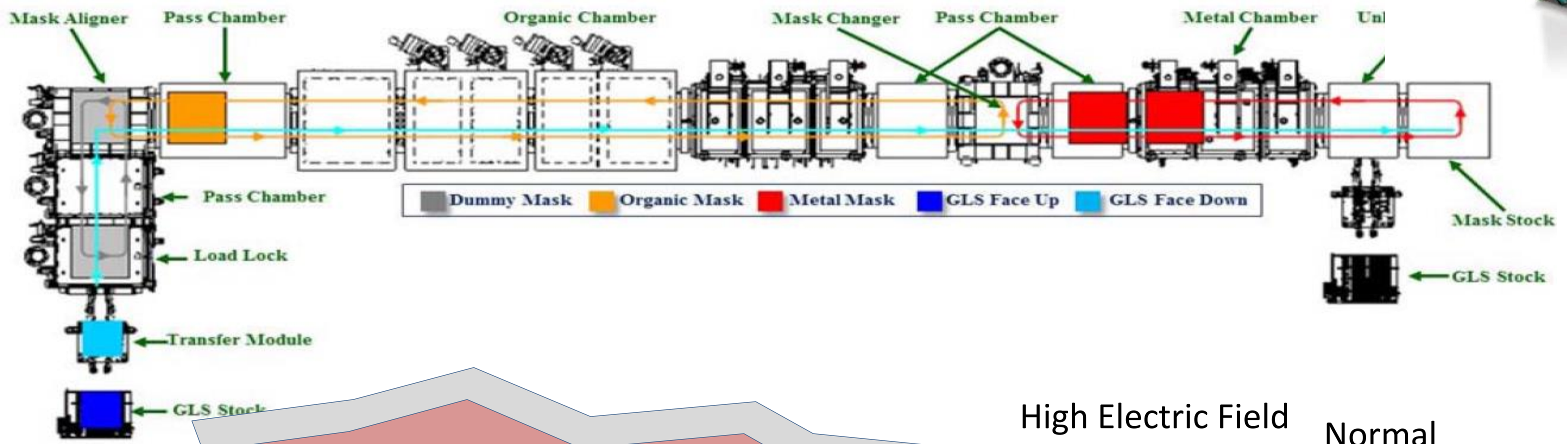


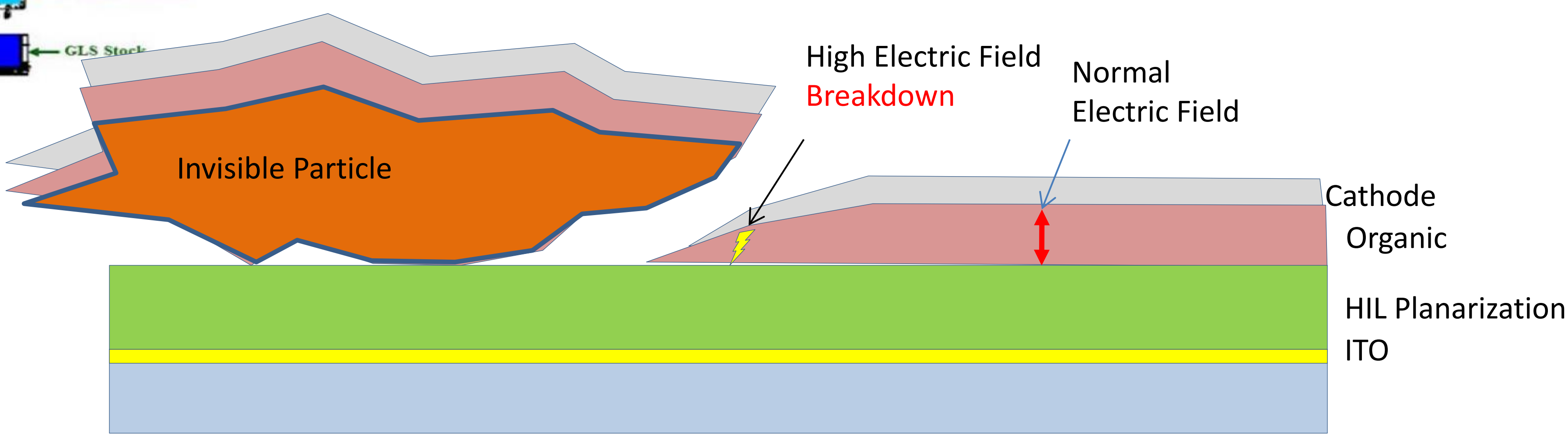
Particles After HIL

Particles can form inside OLED coater

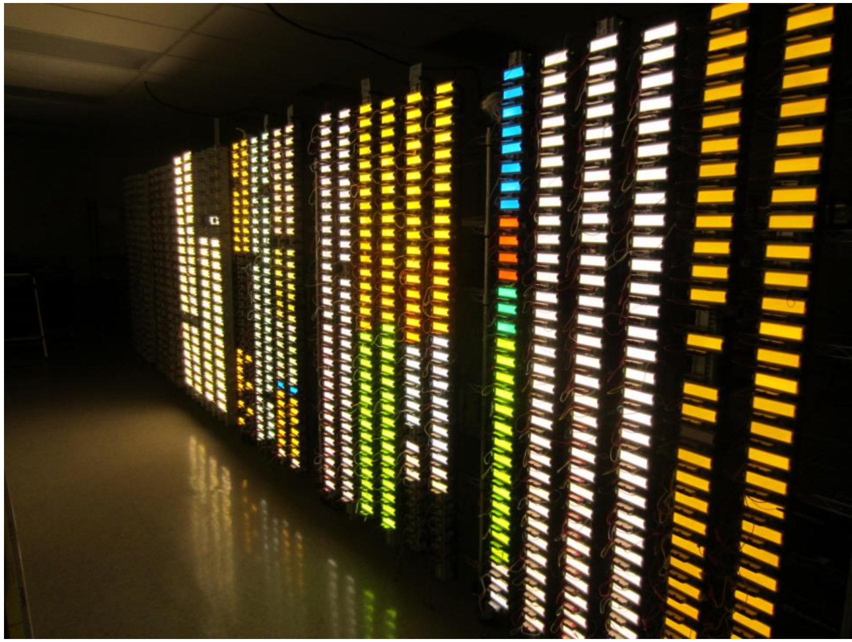


Sunic G5





Improving Reliability



OLEDWorks reliability test stations

- 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.
- **<u>Conclusion</u>** – 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 warrantee costs
- We recommend these as important areas for further manufacturing research and development.