A Smart Active Matrix Pixelated OLED Display

by

Jennifer J. Yu

Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

An OLED display has been fabricated and successfully tested with an external optical feedback circuit to demonstrate improvement in uniformity. In addition, the process of making an integrated system with the optical feedback and OLED display on the same substrate is described. Future work on this solution can include using edge emitted light in the optical feedback, which is discussed and analyzed in this paper.

Thesis Supervisor: Vladimir Bulovic
Title: Associate Professor
Acknowledgments

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Several people played a key role in the completion of the 5x5 OLED display. Criswell Choi designed the original display photomasks, Souren Lefian designed the PC board and adapter for the display, and Aaron Schmidt constructed the display housing. Much of the processing for the 5x5 display took hours upon hours of work in the EML laboratory. Many thanks to MTL staff Kurt Broderick for providing processing help, encouragement, and advice.

Other parts of my thesis were filled in by using pictures from Professor Rubner's microscope and Debbie Mascaro's help. The figures in the introduction are from Professor Bulovic, and Yaakov Tischler first introduced the edge-emitting light feedback concept. I would also like to thank everyone from the LOOE group, in particular John Kymissis and Seth Coe for being great scientific resources.

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This thesis would not have happened without the support of my family. I dedicate this thesis to my mother Shirley Yu, who pushes me to do my best, my older brother Phillip Yu, who looks out for me, and my father, Michael Yu, who just wants me to be happy.

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## Contents

1 Introduction: Why Make OLED Displays? .............................................................. 15
   1.1 Limitation of current technology .............................................................. 15
   1.2 Applications ............................................................................................... 16

2 Background and Motivation .............................................................................. 17
   2.1 OLEDs ......................................................................................................... 17
       2.1.1 Structure ............................................................................................ 17
       2.1.2 Operation ........................................................................................... 17
       2.1.3 Properties ......................................................................................... 19
   2.2 OLED Displays ............................................................................................ 20
       2.2.1 Lifetime .............................................................................................. 20
       2.2.2 Sources of Non-uniformity ................................................................. 20
   2.3 Correcting for Aging Non-uniformities in OLED Displays .......................... 21
       2.3.1 Electrical Feedback ............................................................................ 21
       2.3.2 Philips Optical Feedback Solution ....................................................... 22

3 MIT Optical Feedback Solution ....................................................................... 25
   3.1 Feedback Design ......................................................................................... 25
   3.2 Analysis ...................................................................................................... 25
   3.3 Implementation .......................................................................................... 32
       3.3.1 External Feedback Demonstration ....................................................... 32
       3.3.2 Integrated Display .............................................................................. 33
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>How an OLED works</td>
<td>18</td>
</tr>
<tr>
<td>2-2</td>
<td>Band Energy Diagram of an OLED</td>
<td>18</td>
</tr>
<tr>
<td>2-3</td>
<td>Dependence of IV characteristics on Temperature [1]</td>
<td>19</td>
</tr>
<tr>
<td>2-4</td>
<td>Temperature distribution of (a) vertical and (b) horizontal 10x10cm² display [2]</td>
<td>21</td>
</tr>
<tr>
<td>2-5</td>
<td>OLED Lifetime Intensity and Voltage Change [3]</td>
<td>22</td>
</tr>
<tr>
<td>2-6</td>
<td>Philips optical feedback solution [4]</td>
<td>23</td>
</tr>
<tr>
<td>2-7</td>
<td>Projected lifetime for Philips optical feedback solution [4]</td>
<td>23</td>
</tr>
<tr>
<td>3-1</td>
<td>Feedback Idea</td>
<td>26</td>
</tr>
<tr>
<td>3-2</td>
<td>Feedback Circuit</td>
<td>26</td>
</tr>
<tr>
<td>3-3</td>
<td>Current Density vs. Voltage of an aged and unaged OLED</td>
<td>29</td>
</tr>
<tr>
<td>3-4</td>
<td>Luminance vs. Current Density of an aged and unaged OLED</td>
<td>29</td>
</tr>
<tr>
<td>3-5</td>
<td>Linear plot of current density vs. luminance of an aged and unaged OLED</td>
<td>30</td>
</tr>
<tr>
<td>3-6</td>
<td>Projected Lifetime with MIT Optical Feedback</td>
<td>30</td>
</tr>
<tr>
<td>3-7</td>
<td>Projected Current with MIT Optical Feedback</td>
<td>31</td>
</tr>
<tr>
<td>3-8</td>
<td>Projected Efficiency with MIT Optical Feedback</td>
<td>31</td>
</tr>
<tr>
<td>3-9</td>
<td>Projected Power Efficiency with MIT Optical Feedback</td>
<td>32</td>
</tr>
<tr>
<td>3-10</td>
<td>External feedback setup</td>
<td>33</td>
</tr>
<tr>
<td>3-11</td>
<td>Cross Section of OLED Display for External Feedback</td>
<td>33</td>
</tr>
<tr>
<td>3-12</td>
<td>Silicon Chip Design for Integrated Display</td>
<td>34</td>
</tr>
<tr>
<td>4-1</td>
<td>Process layout</td>
<td>36</td>
</tr>
</tbody>
</table>
4-2 Three photolithographic masks: (a) ITO pads (b) gold electrodes (c) electrode passivation and pixel dividers ........................................... 37
4-3 Top view of photolithographic Masks .................................................. 37
4-4 Alignment Marks on Substrate ............................................................. 38
4-5 Exposed electrode .............................................................................. 39
4-6 (a) An ITO pixel with gold residue from metal lift off process and (b) a clean pixel .................................................................................. 40
4-7 Shadowing effect of metal to ITO .......................................................... 40
4-8 Blown out pixel .................................................................................... 41
4-9 Chemical structure of PEDOT [10] ....................................................... 41
4-10 OLED display on PC board ................................................................. 42
4-11 Back view of OLED display in protective housing .............................. 42
4-12 Front view of OLED display in protective housing ......................... 42
4-13 OLED pixel testing setup ................................................................. 43
4-14 IV characteristic of an OLED pixel ................................................... 43
4-15 External quantum efficiency of an OLED pixel ................................. 44
4-16 OLED feedback demo ................................................................. 45

5-1 Process Outline .............................................................................. 48
5-2 Sample photomask for Integrated Display ........................................ 49
5-3 Silicon Chip ....................................................................................... 49
5-4 Steps to mount chip on holder: (a) application of polyimide (b) and (c) placement of chip in holder (d) removal of polyimide (e) mounted chip on holder ................................................................. 50
5-5 Thin silicon shadowmask ................................................................. 51
5-6 Photolithography of chip ..................................................................... 52
5-7 Photolithography pixel closeup ............................................................ 53
5-8 Packaged integrated display .............................................................. 54

6-1 Index matching material (a) surface mounted and (b) edge mounted captures waveguided light that is normally trapped in glass layer ......................... 56
<table>
<thead>
<tr>
<th></th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-2</td>
<td>Photodetectors mounted on the edge of a display</td>
<td>57</td>
</tr>
<tr>
<td>6-3</td>
<td>Edge Emitted Light Feedback</td>
<td>57</td>
</tr>
<tr>
<td>6-4</td>
<td>Peripheral Surface Emitted Light Feedback</td>
<td>58</td>
</tr>
<tr>
<td>6-5</td>
<td>Dependence of $\phi_{surface}/\phi_{edge}$ on current density [8]</td>
<td>59</td>
</tr>
<tr>
<td>6-6</td>
<td>Laser Experiment Setup</td>
<td>60</td>
</tr>
<tr>
<td>6-7</td>
<td>Detected light from laser source to group of pixels</td>
<td>61</td>
</tr>
</tbody>
</table>
List of Tables

A.1  Fabrication of 5x5 OLED Display  ........................................ 66
A.2  Basic Cleaning Procedure  .................................................... 66
A.3  PDMS mold Procedure  ......................................................... 67
Chapter 1

Introduction: Why Make OLED Displays?

1.1 Limitation of current technology

Liquid Crystal Displays (LCDs) dominate today’s flat panel display market. LCDs are not emissive, using white backplane lighting through color filters to produce the red, green, and blue (RGB) for color displays. An electric field orients the liquid crystal material, allowing backplane lighting to reach the viewer. This scheme only allows for a narrow viewing angle, especially in the vertical direction and has a reduction of efficiency in the actual backplane lighting which must travel through filters to reach the viewer. In the worst case of a dark screen, the backplane lighting remains on while the liquid crystal allows only a small fraction of the light to escape. In addition, LCDs are limited by how fast the liquid crystal can switch with the applied electric field. As a consequence, the refresh rate of the LCD is limited, which may produce ghosting. Ghosting occurs when objects move faster than the refresh rate of the screen and artifacts of the old image can still be seen while the image is in motion.

In contrast, OLEDs are fully emissive. As a consequence, they do not have a viewing angle problem, and OLEDs are more efficient than LCDs. OLEDs have quick response time (1e-6 seconds) and do not have ghosting issues, therefore being a promising candidate for
television displays. If developed in industry, fabrication of OLED displays will be relatively inexpensive and easily scaled to large areas. An additional advantage is that OLED displays are thinner than LCDs and can be fabricated on flexible substrates.

One might think inorganic Light Emitting Diodes (LEDs) are a promising technology since they have stability properties that OLEDs lack as an emerging technology. However, LED fabrication does not allow for an RGB pixel on one substrate since the substrate material produces the different colors. Therefore, a color display made from LEDs must be tiled out of diced RGB LEDs which is costly and therefore not commercially viable.

1.2 Applications

One application where OLEDs have a clear advantage over LCDs is portable computing. OLED displays are already more efficient than LCDs. In addition, OLEDs are a rising technology and promise much better efficiencies in the future. With applications such as video phones, OLEDs provide a better alternative for a quick motion display that LCDs cannot offer. Perhaps the strongest argument is simply that emissive OLED displays look better than the filtered backplane lighting of LCDs.

Future applications that can only be made possible with OLED technology will be discussed as follows. Transparent OLEDs (TOLEDs) give promise to applications such as window, glasses, or car windshield displays. Flexible OLEDs create ideas a variety of applications. For instance, a display that can be rolled out of a pen, bright clothing displays for construction workers and displays on commercial packaging for advertisements, instructions or expiration dates. While LCDs are a mature technology and have limited application, OLEDs give promise to future applications and growth in the display technology industry.
Chapter 2

Background and Motivation

OLEDs are a promising alternative for thin, low-power, portable computing displays. Compared to LCDs which currently dominate the market, OLEDs are more efficient, brightly emissive, and have no refresh rate or viewing angle limitations. However, significant improvement in OLED display lifetime is necessary to replace LCDs as a flat-panel technology.

2.1 OLEDs

2.1.1 Structure

A typical OLED is made of two electrodes which surround an electron transporting layer (ETL) and hole transporting layer (HTL). In figure 2-1, a green OLED is shown with an indium tin oxide (ITO) anode, magnesium-silver cathode, aluminum tris-8-hydroxyquinoline (Alq3) ETL, and N,N'-diphenyl-N,N'-bis(3-methylphenyl)-1,1-biphenyl-4,4'diamine (TPD) HTL.

2.1.2 Operation

When a positive bias is placed on the ITO relative to the magnesium-silver, holes travel through the TPD layer and electrons travel through the Alq3 layer. The electrons and holes meet at the interface of the two materials, shown as the recombination region in figure 2-2.
If the charges happen to land on the same molecule, the molecule forms an excited state known as an exciton. When an exciton relaxes, it may release energy in the form of light.

Figure 2-1: How an OLED works

Figure 2-2: Band Energy Diagram of an OLED
2.1.3 Properties

A typical OLED has the following luminance, current, and voltage relationships:

\[ I \propto V^m \]  \quad (2.1)
\[ L \propto J^n \]  \quad (2.2)

where \( L \) = luminance, \( I \) = current density, and \( V \) = voltage. Current is related to voltage by a high exponent \( m = 6 \) to \( 9 \). Luminance and current are linearly related with \( n = 1 \). From equation 2.1 and 2.2, a small change in voltage results in a large change in current and luminance. For this reason OLED displays are typically current driven instead of voltage driven.

In addition, the relationship in equation 2.1 changes with temperature as shown in Figure 2-3.

![Figure 2-3: Dependence of IV characteristics on Temperature [1]](image.png)
2.2 OLED Displays

2.2.1 Lifetime

The lifetime of an OLED is measured by the amount of time it takes an OLED operated at constant current to decrease to half its initial brightness \((T_{1/2})\). Similarly, OLED display lifetime is measured by turning on all pixels and finding \(T_{1/2}\) of the display. However, this lifetime measurement does not take into consideration pixel-to-pixel non-uniformity. As a result, a display will have a shorter useful lifetime than that of its individual pixels.

2.2.2 Sources of Non-uniformity

Initial non-uniformity of an OLED display occurs with variation of the threshold voltage \((V_t)\) in thin film transistor (TFT) pixel drivers. Philips researchers claim a 5% intensity variation at video brightness due to variation in \(V_t\) for Poly-LED displays. As a remedy, Philips uses a circuit that compensates for either current or voltage through the TFT. [4]

Other sources of non-uniformities occur with changes in the \(LIV\) relationships for individual pixels. The \(IV\) relationship changes with temperature, which is affected by ambient conditions and display operation. An operating display has a temperature distribution that depends on the dimensions and angled position of the display. The maximum temperature for a vertical display occurs in the center of the top region of the display. In comparison, a horizontal display will have its maximum temperature in the middle of the display. [2] Figure 2-4 shows the temperature distribution for various display conditions.

The biggest source of non-uniformity occurs with degradation of an OLED pixel. Figure 2-5 shows a phosphorescent OLED degrading with time. [3] This data shows that an OLED run at constant current will decrease in intensity and increase in voltage. Because displays are normally constant current driven and the \(LI\) relationship changes with aging, pixel-to-pixel non-uniformities occur as pixels degrade at different rates according to usage.

Currently there is no standard for measuring the lifetime of a display, but a 10% pixel to pixel intensity variation is easily observed. We arbitrarily choose this value to measure the
Figure 2-4: Temperature distribution of (a) vertical and (b) horizontal 10x10cm² display [2] lifetime of a display. [4] In the worst case, a pixel may be in constant use while its neighbor is never in use. Therefore, the minimum display lifetime can be estimated as a 10% intensity decrease of the display with all pixels on. A study at Philips Research Laboratories on Poly-LED displays shows a 10% intensity decrease after 400 hours of use compared to $T_{1/2} = 10,000$ hours. [4]

2.3 Correcting for Aging Non-uniformities in OLED Displays

2.3.1 Electrical Feedback

A potential solution to this problem is to monitor the voltage drift of a constant-current OLED pixel. The voltage drift can be correlated with luminance, and then compensated to produce a more uniform display. Although this method can improve display performance, it
does not account for the effect of temperature on the $IV$ relationship and is therefore limited in effectiveness. [1] [2] A more reliable solution can be obtained by using optical feedback, which directly monitors the actual light output of individual pixels. In this scheme, the $LIV$ relationships can vary, but the output will remain uniform.

### 2.3.2 Philips Optical Feedback Solution

Recently, Philips Research Laboratories implemented an optical feedback solution for a Poly-LED display. [4] The circuit schematic of this solution is shown in Figure 2-6. The TFT driver of each pixel is regulated by the amount of light sensed by a corresponding pixel photodetector. When the photodetector detects light from the OLED pixel, it generates a current that discharges a reference voltage connected to the gate of the TFT driver. When the reference voltage discharges below $V_t$, the TFT driver stops conducting and the pixel turns off. A bright pixel will induce a large current through the photodetector, allowing the reference voltage to discharge quickly to switch the pixel off. Within a frame cycle, the viewer interprets a dim pixel with a long time duration and a bright pixel with shorter time
Poly-LED Display Lifetime

This solution is limited by a refresh rate of 60 hertz for the frame cycle and requires that the pixel does not degrade past the compensation limit. With this optical solution, the display degradation is initially retarded, but begins to degrade rapidly as more pixels reach the limit of frame-time compensation. Figure 2-7 shows a simulated lifetime projection of this solution. A Poly-LED display using this feedback solution will reach a 10% intensity decrease in 15,000 hours of usage [4]. An additional factor to consider is the pixels are not on during an entire frame cycle, and therefore need to be operated at higher currents to maintain video brightness.

Figure 2-6: Philips optical feedback solution [4]

Figure 2-7: Projected lifetime for Philips optical feedback solution [4]
Chapter 3

MIT Optical Feedback Solution

3.1 Feedback Design

At MIT, we are pursuing our own feedback solution. Figure 3-1 shows a schematic of the basic idea, and Figure 3-2 shows the details the feedback circuit. This feedback scheme changes the drive current of a pixel to maintain a uniform brightness for OLED displays [6] [7]. An op-amp is used with a negative feedback capacitor to integrate the light output of the photodetector. This voltage is then placed on the gate of the TFT driver and to drive the OLED at an appropriate current.

Unlike the Philips solution, which gradually degrades over time and is limited by the frame refresh rate, our solution is limited by pixel lifetime, driving voltage range, and will remain uniform until pixel failure. In addition, our solution is driven with a lower initial current and therefore starts with a slower degradation rate than the Philips solution. [3]

3.2 Analysis

To estimate the viability of our solution, we use existing data from a 2003 lifetime study of phosphorescent OLEDs from Kwong et. al.. [3] We chose this data because it is recent and representative of situations to which our solution can be applied. In Kwong’s experiment,
Figure 3-1: Feedback Idea

Figure 3-2: Feedback Circuit
three phosphorescent OLEDs were operated under constant current with initial luminance $L_o = 200, 500, 1000$. Kwong verifies a suggested $T_{1/2} \propto 1/L_o$ relationship of fluorescent OLEDs for phosphorescent OLEDs. [5] Using this relationship, a 50,000 hour lifetime is extrapolated at video brightness (100 cd/m²).

Figure 3-4 and 3-3 shows data taken before and after Kwong’s lifetime experiment for $L_o = 1000$ cd/m². Figure 3-4 shows that the relationship between luminance and current density ($J$) remains linear over time. The $JV$ relationship changes significantly, but in our favor. The exponent becomes larger with time, indicating that the initial $JV$ relationship is an overestimate of the necessary voltage needed to maintain a particular brightness. These relations can be written as equations

\[ L_{kwong}(t) = C_{jl}(t) * J_o \]  
\[ J_o = C_{ju}(t) * [V_{kwong}(t)]^{n(t)} \]

where $L_{kwong}(t)$ and $L_o$, $J_o$, and $V_o$ (initial $L$, $J$, and $V$) are from Kwong’s original data. $C_{jl}(t)$ and $C_{ju}$ are constants relating $J_o$, $L$, and $V_o$. Combining equations (3.1) and (3.2), $L_{kwong}(t)$ is related to $V_{kwong}(t)$ by

\[ V_{kwong}(t) = \left[ \frac{1}{C_{jl}(t) * C_{ju}(t)} * L_{kwong}(t) \right]^{\frac{1}{n(t)}} \]  

Given the initial normalized luminance output, driving the OLED by a factor of $\frac{L_o}{L_{kwong}(t)}$ will produce the initial brightness. Substituting the new luminance into equation (3.3), the new voltage becomes

27
Using these equations, an estimate can be made on the lifetime of a OLED given a certain voltage range. The worst case estimate on the driving voltage occurs with the minimum value of $n(t)$, which is also the initial $JV$ relationship. Figure 3-6 shows the voltages needed to extend the lifetime of a OLED. With the 12 volt maximum range, $L_o = 1000$ has a lifetime of 6,500 hours, $L_o = 500$ has lifetime of 17,000 hours, and $L_o = 200$ has lifetime of 30,500 hours. In comparison, without feedback, the $L_o = 200$ cd/m² can have a 10% pixel-to-pixel variation in brightness in 3,000 hours. Although the Philip’s solution has a simpler feedback circuit, our solution offers significant life extension and a completely uniform display.

Figure 3-7 shows the projected current density. This is calculated using equation (3.1), with a constant $L_o$ and approximating $C_{ji(t)}$. Figure 3-5 shows that $C_{ji(t)}$ of $Lo = 1000$ will change by a significant amount; the current density projection may be off by a factor of approximately 1.76 for $Lo = 1000$. Using this as a worst-case scenario, the new projected current density can be estimated as

$$J_{new} = 1.76 \times J_o/L_{kwong}(t)$$

The projected luminance and power efficiency of this feedback scheme are showed in Figure 3-8 and 3-9. The average power efficiency is calculated with a trapezoidal integral estimate as $L_o = 1000$ as 1.940, $L_o = 500$ as 2.451, and $L_o = 200$ as 2.976 (Lumens/Watt)/Hours.
Figure 3-3: Current Density vs. Voltage of an aged and unaged OLED

Figure 3-4: Luminance vs. Current Density of an aged and unaged OLED
Figure 3-5: Linear plot of current density vs. luminance of an aged and unaged OLED

Figure 3-6: Projected Lifetime with MIT Optical Feedback
Figure 3-7: Projected Current with MIT Optical Feedback

Figure 3-8: Projected Efficiency with MIT Optical Feedback
3.3 Implementation

Implementation of this solution consists of two phases. The first phase is a proof of concept demonstration with external feedback circuitry. The second phase is an integrated display.

3.3.1 External Feedback Demonstration

The proof of concept demonstration consists of an external feedback system, an OLED display, and a video camera to monitor the light output of the display. The setup is shown in Figure 3-10.

Eko Liwuwandi designed the external feedback system, and I worked on the fabrication of an 5x5 active matrix OLED display. A cross sectional layout of this display is shown in Figure 3-11.
3.3.2 Integrated Display

In reality, a display should be one unit and have a built-in optical feedback circuit. The integrated display will contain the feedback and display on the same silicon substrate. The layout of the substrate is shown in Figure 3-12. The integration requires TOLED pixels because of their ability to emit light from the front and back. The back side of the TOLED faces a photodetector that monitors the light output for the feedback circuitry.
Figure 3-12: Silicon Chip Design for Integrated Display
Chapter 4

Fabrication of OLED Display for External Feedback

4.1 Process Outline

The major steps in the fabrication process are shown in Figure 4-1 and detailed in Section A.1. This process requires three photolithography masks shown separately in 4-2 and superimposed in Figure 4-3. The first mask patterns the bottom ITO anodes for the display. Since this pre-deposited ITO has a resistivity of 20 $\Omega/\text{cm}$, the second mask patterns metal electrodes to contact each pad. The third mask patterns photoresist on top of the electrodes for passivation and defines the active pixel area of 4.167 x 4.167 mm$^2$.

4.2 Process Details

All processing was done in the Exploratory Materials Laboratory (EML) and the Laboratory of Organic Optoelectronics (LOOE) at MIT. The processing of the OLED substrate took place in EML while the organic deposition was performed in LOOE.
Figure 4-1: Process layout
Figure 4-2: Three photolithographic masks: (a) ITO pads (b) gold electrodes (c) electrode passivation and pixel dividers

Figure 4-3: Top view of photolithographic Masks
4.2.1 Cleaning Procedure

The cleaning procedure used is detailed in Section A.2. A cursory clean of the substrate is sufficient due to the large feature size of the display.

4.2.2 Photolithography

Figure 4-4 shows the result from the completed mask alignment steps. Alternation was made to the third mask because it failed to passivate the electrodes. The exposed electrode is shown in Figure 4-5.

4.2.3 Metal Electrode Deposition

The chromium layer provides a good adhesion for gold to the glass substrate. Oxygen plasma treatment of the substrate prior to E-beaming is required for a good bond between chromium and glass. Sufficient chromium is needed to prevent gold removal during the metal liftoff, but too much chromium causes gold particles to remain on the substrate’s emissive area. A bilayer of 200 Å of chromium and 600 Å of gold gave reasonable results. Figure 4-6 shows a clean pixel on the right, but gold particles could still be observed on some pixels as shown
on the left. This may have led to shorting problems with OLED pixels.

4.2.4 PEDOT

Shorting problems also occurred due to shadowing effects during the final organic and metal evaporation. This effect is shown in Figure 4-7.

Testing right after deposition led to non-working or blown out pixels due to high testing current. Figure 4-8 shows a blown out OLED pixel. Note that the blown out area is concentrated along the edges of the pixel, indicating that the shadowing effect contributed to the shorting of the device.

Testing that occurred a week after leaving the display in a nitrogen glove box resulted in some working pixels. These pixels did not previously work, which leads to a hypothesis that over time the organic materials may have absorbed moisture and caused the cathode to separate from the anode.

The solution to this problem is 3,4, Polyethylene dioxythiophene Polystyrene Sulfonate (PEDOT), shown in Figure 4-9. PEDOT is a conductive polymer that is used to improve metal contacts for OLEDs. In this case, PEDOT provides an insulating layer on the surface of the substrate to prevent electrical shorts. After application of PEDOT, all pixels of the display turned on with no problems.
Figure 4-6: (a) An ITO pixel with gold residue from metal lift off process and (b) a clean pixel

Figure 4-7: Shadowing effect of metal to ITO
4.2.5 Packaging

The finished display is packaged with UV-curable epoxy and a glass slide. Using standard epoxy, the display is mounted and then gold wire bonded to a PC board that interfaces with the external feedback circuitry. This PC board shown in Figure 4-10 connect the electrodes of a display to a 26 pin cable. This cable connects to an adapter that converts the wiring to be compatible with the feedback circuitry. After gold wire bonding the display to the PC board, a display housing was constructed to protect the bondwires. Figure 4-11 and 4-12 show the back and front of the display in the protective housing.

4.3 Results

The unpackaged OLED pixels were tested with probes connected to a current source shown in Figure 4-13. The $IV$ characteristic of a pixel is shown in Figure 4-14, and the external quantum efficiency of a pixel is shown in Figure 4-15.
Figure 4-10: OLED display on PC board

Figure 4-11: Back view of OLED display in protective housing

Figure 4-12: Front view of OLED display in protective housing
Figure 4-13: OLED pixel testing setup

Figure 4-14: IV characteristic of an OLED pixel
4.3.1 Integration with Feedback System

Testing was done with the external feedback system. In Figure 4-16, the display on the left is purposely made non-uniform. By allowing the feedback to compensate for the non-uniformities, a perfectly uniform display on the right is the result.
Figure 4-16: OLED feedback demo
Chapter 5

Fabrication of Integrated Display

5.1 Process Outline

OLEDs will be processed on top of a silicon chip containing photodetectors with silicon feedback circuitry. The process outline is shown in Figure 5-1.

This process requires one photolithographic mask to pattern the ITO bottom pixels. Since the ITO etch will also attack the aluminum pads on the chip, a protective photoresist layer is patterned as well. A sample photolithographic mask is shown in Figure 5-2. Initial and final shadowmask steps are also needed to protect the aluminum chip pads shorting due to ITO sputtering.

All processing is done in Technology Research Laboratory (TRL) and LOOE. TRL provides a cleaner environment than EML to define 2 μm photolithographic features of the chip.

5.2 Process Details

5.2.1 Substrate Holder

The substrate shown in Figure 5-3 is approximately 1.2 x 7.6 mm². A substrate holder is required to protect the chip from process handling. Several considerations arose when
Figure 5-1: Process Outline

1. Sputter ITO anode
   OLED feedback circuitry on Si

2. Mask Alignment to Si pattern
   UV Light
   Photoresist Exposure

3. Development

4. ITO Etch
   DI, HCl, Nitric Acid (4:3:1)

5. Resist Removal
   (Acetone rinse & Oxygen Plasma)

6. Sputter ITO cathode
   Evaporate Active Organic Thin Films
designing a chip holder.

For sputtering, the holder does not need to be rigid, and can be made from polydimethylsiloxane (PDMS). PDMS has the advantage of surface adhesion to the shadowmask allowing ease of alignment. A sacrificial chip stuck to the bottom of a glass petri dish served as the negative mold for the holder. The details of making the PDMS holder can be found in Section A.3.

For photolithography, the holder needs to be rigid to obtain a uniformly spun layer of photoresist. After trying a silicon hydrofluoric acid etch and construction of a holder out
of silicon pieces, the best alternative is to use the Surface Technology System (STS) deep silicon etching machine in TRL. The STS produces an anisotropic etch of silicon using SF$_6$ and C$_4$F$_8$ process gases. In addition, the etch depth can be controlled if the process is interrupted to monitor the rate during the run.

In this case, 250 μm wells were etched in silicon to hold the chip. Polyimide is used as the adhesive for the chip in the holder. Figure 5-4 shows the adhesion application and removal process. To apply adhesive, a small amount on a foam tip is rubbed over the holder and the chip is placed in the trench. Once the adhesive is cured, the chip and the holder become a permanent unit used through all processing steps. Additional caution needs to be taken when cleaning the substrate and holder since polyimide has a tendency to peel off as a layer. This can be avoided by carefully removing the polyimide from the surface of the substrate without disturbing the polyimide adhesive between the chip and holder.

Figure 5-4: Steps to mount chip on holder: (a) application of polyimide (b) and (c) placement of chip in holder (d) removal of polyimide (e) mounted chip on holder
5.2.2 ITO deposition

Shadowmask alignment is necessary for ITO deposition to prevent shorting of the analog and digital pads on the chip. These pads can be seen in Figure 5-3 on the left and bottom side of the chip. A good shadowmask will produce a clean edge and allow uniform deposition of the ITO. Thin silicon is an excellent shadowmask for these reasons. Diced silicon produces a clean edge and a thin mask will reduce the shadowing effect for uniform deposition.

Positioning the shadowmask by hand and verifying the location through an optical microscope is sufficient for alignment within 300 μm. Heat resistant Kapton tape is used to form a right angle mask out of two pieces of diced silicon. This allows coverage of the aluminum pads so they are not shorted during ITO deposition. Figure 5-5 shows the result of shadowmask alignment on the feedback chip.

![Figure 5-5: Thin silicon shadowmask](image)

5.2.3 Photolithography

Figure 5-2 shows a photolithographic mask to be used for patterning ITO on top of the chip photodetectors. The structures on the top right hand corner are test pixels. The display consists of 16 x 128 pixels. In addition, photoresist is patterned on top of aluminum pads for
protection during the ITO etch. Figure 5-6 shows photolithography on the chip, and Figure 5-7 shows a close up of a photolithography on a pixel.

![Photolithography of chip](image)

**Figure 5-6: Photolithography of chip**

### 5.2.4 Organic deposition and final ITO sputtering

This last deposition step requires the same shadowmask alignment from the first ITO deposition. Because sputtering is an aggressive deposition that may disturb the organic layers, a reduced rate of 3 Å per minute is used for the first 100 Å of ITO. The next 1400 Å sputtered at a rate of 24 Å per minute.

### 5.2.5 Packaging

The finished integrated display is mounted onto a device package with silver paste. After gold wire bonding the chip pads to the package pads, an airtight seal is made over the package with a UV-curable epoxy and glass slide. Figure 5-8 shows a sample packaged chip.
Figure 5-7: Photolithography pixel closeup
Figure 5-8: Packaged integrated display
Chapter 6

Edge Emitted Light Feedback Idea

The integrated display described in the previous chapter requires TOLED deposition on top of photodetectors. This approach, although conceptually straightforward, significantly reduces the efficiency of the display. The reflective metal anode used in uncompensated OLED displays increases the brightness of the display and the external quantum efficiency.

An alternative is to use feedback on the edge emitted light of the OLED. Equation 6.1 is an application of Snell’s Law for the glass and air interface of an OLED display. The index of refraction of glass, $n_{\text{glass}}$, is 1.4 while $n_{\text{air}} = 1$.

$$n_{\text{air}} \cdot \sin(\theta_{\text{air}}) = n_{\text{glass}} \cdot \sin(\theta_{\text{glass}}) \quad (6.1)$$

Light gets trapped in the glass when $\theta_{\text{air}}$ becomes greater than 90°. Equation 6.1 becomes

$$\theta_{\text{critical}} = \arcsin(1/1.4) \quad (6.2)$$

$$\theta_{\text{critical}} \approx 46^\circ \quad (6.3)$$

Thus, total internal reflection will occur with any light emitted at an angle greater than $\theta_{\text{critical}}$ to the normal surface. However, this internal light can be captured if an index matching material is mounted on the surface or edge of the glass as shown in Figure 6-1.
Figure 6-1: Index matching material (a) surface mounted and (b) edge mounted captures waveguided light that is normally trapped in glass layer.

By mounting photodetectors with index matching gel in these position, the internal or edge emitted light can be captured and used in a similar circuit to Figure 3-2 to produce a more uniform display. Figures 6-3 and 6-4 show an edge and surface feedback scheme for one pixel, and Figure 6-2 shows an edge mounted photodetector setup for a display.

6.1 Analysis

Placing the photodetectors on the side of the display differs from the original scheme. Previously, the integrated feedback had a photodetector underneath each pixel, allowing real-time and instantaneous calibration of the display. With edge photodetectors, the feedback cannot occur while the user is viewing the display. Instead, individual pixels must be turned on one at a time to calibrate the display. The original feedback scheme stores a single reference value for the pixel brightness. With edge emission, an additional value, the ratio \( \phi_{\text{surface}} \) and edge \( \phi_{\text{edge}} \) electroluminescent intensities needs to be stored to determine the surface light emission of each pixel.
Figure 6-2: Photodetectors mounted on the edge of a display

Figure 6-3: Edge Emitted Light Feedback
Using the initial $\phi_{surface}/\phi_{edge}$ relationship for the feedback will give reasonable results. $\phi_{surface}/\phi_{edge}$ depends on the current density through the OLED pixel. Using the constant brightness feedback scheme forces the pixels to be driven at different current densities during their lifetime. This change, which depends on the $1/L(t)$ factor of surface emission, will change less than an order of magnitude. Using equation 3.1, the corresponding current change will also be less than an order of magnitude. Normal video brightness has current density of approximately 1 mA/cm$^2$. As seen in Figure 6-5, the delta in $\phi_{surface}/\phi_{edge}$ for 1 to 10 mA/cm$^2$ stays constant to within 5% [8]. Using a worst-case estimate, this accounts for a 3% error in the ratio in $\phi_{surface}/\phi_{edge}$. This error is less than the 10% uniformity error for displays, but should be corrected for a better display. To get a better feedback result, the flux ratio at different current densities can be collected during the initial calibration and stored. As an OLED pixel degrades, the feedback controller can monitor the current density and use the appropriate ratio to find the surface emission.

Limitations to this feedback scheme include external light interference, the detectability of an individual pixel with a side photodetector, and the calibration time of a display. First, external light could limit the effectiveness of a display if it interferes with the calibration. Second, the sensitivity of a photodetector to a pixel will ultimately limit the possible size
of a display as well as the calibration time. Finally, the calibration time of a display has to correct for non-uniformities should be reasonable to the consumer, akin to a two second degaussing of a cathode ray tube display.

External light will not have a large effect to this feedback scheme. Data has been taken on a Kodak AM500L evaluation OLED active matrix display. On the front periphery of the display, a silicon photodiode with a PDMS layer over the active region was pressed against the display glass. The experimental setup is shown in Figure 6-6. The photodiode measured the light first from a cluster of white OLED pixels and then a red laser centered at roughly the same set distance from the detector. The angle of the display was changed horizontally relative to the laser beam, and the greatest light reading came from the laser being directly on the front of the display. Using a laser of 12 \( \mu \)watts and a the pixel cluster brightness of 85 nanowatts, the detected value from the photodetector is on the same order of magnitude. Therefore, a display at video brightness can compete with a laser 1000x brighter than its pixels for photodetector measurement. If ambient light does become an issue, one solution is to take two measurements and subtract out the ambient light. Another solution would be to calibrate the OLED display when dark cover is put on the display. In the case of a

Figure 6-5: Dependence of \( \phi_{\text{surface}}/\phi_{\text{edge}} \) on current density [8]
laptop, the display can be calibrated when the laptop is closed.

![Figure 6-6: Laser Experiment Setup](image)

The edge emitted light depends entirely on the radiative modes of the OLED. Radiative light implies that intensity drops off as a function of distance. A pixel at the center of a display will have less edge emitted light than a pixel closer to the edge of a display. Any photodetector along one edge of the display will end up getting 1/4 of the internal light output. All this light can be collected if enough time is given to the photodetector to make the measurement. This may affect the calibration time, but now the limit is not the amount of light but the amount of time dedicated to calibration.

The calibration time of the system depends on the number of pixels and photodetectors, the response time of the photodetectors, and the processor clock of the feedback controller. A rough estimation can be made by assuming the simplest setup with one edge photodetector. By current standards, there are approximately one million (1e6) pixels per display. The response time of a silicon photodetector is faster than a microsecond (1e-6). However, due to the distance of a pixel to the photodetector, this figure may need to be modified to give
an adequate amount of time to measure signal. The response time of a typical OLED pixel is around a microsecond (1e-6). Thus, the total calibration time is on the order of a second for the entire display.
Chapter 7

Conclusion

7.0.1 Summary

Optical feedback is a feasible solution for correcting the aging non-uniformities in OLED displays. Our solution has shown a proof of concept demonstration and is well under way for integrated processing. Future work include a proposed edge-emitted light solution which is currently under investigation. This research project demonstrates differential aging of pixels in an OLED display could be sufficiently compensated in enabling the use of OLED technology in applications that require operating lifetimes beyond 10,000 hours.
Appendix A

Procedures
Table A.1: Fabrication of 5x5 OLED Display

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Start with 2x2 inch$^2$ ITO pre-deposited glass substrate</td>
</tr>
<tr>
<td>2</td>
<td>Basic cleaning procedure</td>
</tr>
<tr>
<td>3</td>
<td>Photolithography procedure with Mask 1</td>
</tr>
<tr>
<td>4</td>
<td>ITO etch for 7 minutes in 4:3:1 solution of DI water, HCl, and nitric acid</td>
</tr>
<tr>
<td>5</td>
<td>Basic cleaning procedure</td>
</tr>
<tr>
<td>6</td>
<td>Photolithography procedure with Mask 2</td>
</tr>
<tr>
<td>7</td>
<td>Cr and Au deposition with E-beam onto substrate</td>
</tr>
<tr>
<td>8</td>
<td>Acetone lift off</td>
</tr>
<tr>
<td>9</td>
<td>Basic cleaning procedure</td>
</tr>
<tr>
<td>10</td>
<td>Photolithography with Mask 3</td>
</tr>
<tr>
<td>11</td>
<td>Dice substrate to 1.5x1.5 inch square</td>
</tr>
<tr>
<td>12</td>
<td>Micro 90 and DI water clean. Blow Dry</td>
</tr>
<tr>
<td>13</td>
<td>Filter PEDOT through PTFE</td>
</tr>
<tr>
<td>14</td>
<td>Spin PEDOT on substrate, 3500 rpm for 30 seconds with 10K ramp</td>
</tr>
<tr>
<td>15</td>
<td>Dehydration bake for 5 minutes at 130 to 150 degrees celsius</td>
</tr>
<tr>
<td>16</td>
<td>Position and clamp shadow mask to cover side electrodes</td>
</tr>
<tr>
<td>17</td>
<td>Deposit organic layer: 500 Å TPD and 500 Å Alq3</td>
</tr>
<tr>
<td>18</td>
<td>Deposit metal cathode: co-deposit 500 Å of a 10:1 ratio of magnesium and silver, cap with 500 Å of silver</td>
</tr>
<tr>
<td>19</td>
<td>Package in nitrogen glove box with curable UV epoxy and 1 x 1 inch glass slide</td>
</tr>
<tr>
<td>20</td>
<td>Gold wire bond display to PC board interface</td>
</tr>
<tr>
<td>21</td>
<td>Encase display in protective housing to protect gold electrodes</td>
</tr>
</tbody>
</table>

Table A.2: Basic Cleaning Procedure

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sonicate 5 minutes in .25 solution of Micro-90</td>
</tr>
<tr>
<td>2</td>
<td>Deionized (DI) water rinse</td>
</tr>
<tr>
<td>3</td>
<td>Rub with foam tip .25 solution of Micro-90</td>
</tr>
<tr>
<td>4</td>
<td>DI water rinse</td>
</tr>
<tr>
<td>5</td>
<td>Sonicate 5 minutes with DI water</td>
</tr>
<tr>
<td>6</td>
<td>DI rinse</td>
</tr>
<tr>
<td>7</td>
<td>Sonicate 5 minutes with DI water</td>
</tr>
<tr>
<td>8</td>
<td>DI rinse</td>
</tr>
<tr>
<td>9</td>
<td>Immerse in boiling isopropanol</td>
</tr>
<tr>
<td>10</td>
<td>Blow dry with nitrogen</td>
</tr>
<tr>
<td>11</td>
<td>5 minutes UV clean</td>
</tr>
</tbody>
</table>
### Table A.3: PDMS mold Procedure

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mix 8:1 volume of PDMS with curing agent</td>
</tr>
<tr>
<td>2</td>
<td>Place under vacuum for 5 minutes</td>
</tr>
<tr>
<td>3</td>
<td>Spray mold with Sylgard releasing agent</td>
</tr>
<tr>
<td>4</td>
<td>Pour PDMS in mold</td>
</tr>
<tr>
<td>5</td>
<td>Heat on hotplate at 130 C for 5 minutes</td>
</tr>
<tr>
<td>6</td>
<td>Release solid PDMS from mold</td>
</tr>
</tbody>
</table>
Bibliography


