Flexible Organic ElectroLuminescent Display

Fabrication of a 32x32 Passive-Matrix Display

Author: Josh

Abstract: Building and testing a 32x32 passive matrix electroluminescent display using screen-printing method.
Executive Summary

The Flexible Organic ElectroLuminescent Display (FOELD) project was started as a learning exercise to develop skills as future and emerging engineers. The goal of FOELD was to apply knowledge from the last four years of University to study the effects of electroluminescence and to build a working 32x32 passive-matrix display using an AC driving circuitry. The key applications for FOELD are portable displays, lighting and for use in rescue work.

By studying the display, a theoretical model was built to study the effects, and to tweak the characteristics to move on to the next progression for fabrication. The report discusses the fabrication process, along with some mask design and parameter measurements. It also deals, albeit briefly, with the mechanism of the EL emission. It also discusses the potential problems faced in this cheap and relatively easy-to-manufacture display.

The future of a sustainable and efficient display technology and its numerous applications is examined, with ideas for future development in this area of research.
# Table of Contents

Executive Summary ........................................................................................................ i

Acknowledgments ......................................................................................................... ii

Glossary .......................................................................................................................... viii

List of Tables .................................................................................................................... ix

List of Figures ................................................................................................................... x

Chapter 1 – The FOELD Project .................................................................................. 1

1. Introduction ............................................................................................................. 1

2. Objective .................................................................................................................. 2

   2.1 Passive 32x32 Matrix Display ........................................................................... 2

   2.2 Parameter Extraction ......................................................................................... 2

   2.3 Project Management .......................................................................................... 2

3. Motivation .................................................................................................................. 3

   3.1 Current Display Technology ............................................................................. 3

   3.2 Feasibility as a replacement for paper ............................................................... 4

   3.3 Sustainability ..................................................................................................... 5

Chapter 2 – Professional Practice ............................................................................... 6

1. Health and Safety .................................................................................................... 6

   1.1 WHMIS .............................................................................................................. 6
1.2 Health and Safety ................................................................. 6

2. Engineering Professionalism ................................................... 7

3. Project Management ............................................................... 8

Chapter 3 - Background .............................................................. 10

1. How OELDs Work ................................................................. 10

2. Electrical Model of OELD pixel ............................................. 12

3. Passive and Active Matrix Addressing .................................... 12

Chapter 4 – Building the Mask .................................................. 14

1. Designing the Test Structures and Masks ............................... 14

   1.1 Software ........................................................................ 14

   1.2 Test Structure #1 ......................................................... 14

2. Mask Fabrication Process ....................................................... 16

   2.1 Software – HP Vee ........................................................ 16

   2.2 Emulsion and Screen ....................................................... 17

   2.3 Screen Writing .............................................................. 19

   2.4 UV Exposure ............................................................... 20

   2.5 Washing ....................................................................... 21

3. Designing the Final Display .................................................... 22

   3.1 16x16 vs. 32x32 ............................................................ 22

   3.2 Mask Design ............................................................... 23
3.3 Layering................................................................................................................. 23

4. Display Printing Process ......................................................................................... 24

4.1 Materials Used ..................................................................................................... 24

4.2 Screen Printing ...................................................................................................... 25

4.3 Baking ....................................................................................................................... 27

4.4 Screen Care ............................................................................................................. 28

Chapter 5 – Testing & Results .................................................................................. 31

1. Testing the Display ................................................................................................. 31

1.1 Equipment Set up & Apparatus .......................................................................... 31

1.2 Results ..................................................................................................................... 32

1.2.1 Test Structures #1 ............................................................................................. 32

1.2.2 Test Structures #2 ............................................................................................. 35

1.2.3 16x16 Mask Design #1 ...................................................................................... 38

1.2.4 16x16 Mask Design #2 ...................................................................................... 40

1.2.5 32x32 Mask Design #1 ...................................................................................... 42

1.2.6 32x32 Mask Design #2 ...................................................................................... 43

Chapter 6 – Problems and Solutions ....................................................................... 46

1. Problems .................................................................................................................. 46

1.1 Poor Resolution ..................................................................................................... 46
1.2 Bending........................................................................................................ 46
1.3 Uneven ink deposits................................................................................ 47
1.4 Emulsion peeling...................................................................................... 47
1.5 Misalignment of UV blockers ............................................................... 47
4.2 Misalignment of mask design .............................................................. 48

2. Table of Problems & Solutions ............................................................... 48

Chapter 7 – Improving the Display ............................................................... 49
1. Improving the display ................................................................................ 49
1.1 Using Different Materials ...................................................................... 49

Chapter 8 – Parameter Extraction & Measurements ........................................ 51
1. Equipment Used ........................................................................................ 51
1.1 Setup ............................................................................................................. 51
1.2 Setting up graphs ..................................................................................... 53
1.3 Picking out optimum frequency & voltage...................................... 54

Chapter 9 - Conclusion........................................................................................ 56
1. Discussion.......................................................................................................... 56
2. Future Work and Consideration............................................................. 57
3. Practical Implications.................................................................................... 58
References ...................................................................................................................... 59

Appendix

A - Chemicals – Datasheets and MSDS information

B - Gaant Charts

C – Final 32x32 Mask Design and Finished product

D – Measurements

E – Excel and MATLAB code

F - Graphs
Glossary

**Electroluminescence** – Direct conversion of electric energy to light by a solid phosphor subjected to an alternating electric field.

**PPI** – *(Pixels per Inch)* the measurement of the resolution of a monitor or scanner.

**FPD** - *(Flat Panel Display)* a thin lightweight video display used in laptop and notebook computers and employing liquid crystals, electroluminescence, or a similar alternative to cathode-ray tubes.

**CRT** – *(Cathode Ray Tube)* A vacuum tube in which a hot cathode emits electrons that are accelerated as a beam through a relatively high voltage anode, further focused or deflected electro-statically or electromagnetically, and allowed to fall on a phosphorescent screen.

**AC** – *(Alternating Current)* an electric current that reverses direction at regular intervals, having a magnitude that varies continuously in sinusoidal manner.

**Ionomer** - any of a class of plastics that because of its ionic bonding action is capable of conducting electric current.

**eV** – *(electron-volt)* a unit of energy, equal to the energy acquired by an electron accelerating through a potential difference of one volt and equivalent to $1.602 \times 10^{-19}$ joules.
List of Tables

Table 1. Pixel Size selection for a 32x32 display.. ......................................................... 23
Table 2. Pixel Size selection for a 32x32 display.. ......................................................... 23
Table 3. Specifications for the first set of test structures...............................................32
Table 4. Specifications for the first set of test structures...............................................35
Table 5. Characteristics of the first 16x16 display.........................................................38
Table 6. Characteristics of the second 16x16 display...................................................40
Table 7. Specifications and characteristics of the first 32x32 mask design............ 42
Table 8. Specifications and mask design for the second 32x32 display.............. 43
Table 9. Problems faced during fabrication.. .................................................................48
Table 10. Sample data using 145V driving voltage......................................................53
Table 11. Crosstalk visibility according to the driving voltage.........................55
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Month-by-Month Progress of each team member.</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>A typical single-layer electroluminescent display on substrate</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>A typical multi-layer EL display on substrate</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>Theoretical model of the EL display</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>PM-OLED and AM-OLED</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>Test Structure #1</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>Text Structure Pixel</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>HP Vee software</td>
<td>17</td>
</tr>
<tr>
<td>9</td>
<td>Screen Preparation</td>
<td>18</td>
</tr>
<tr>
<td>10</td>
<td>The PPMT25/5231 Laser</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>UV Exposure and emulsion curing</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>Post-wash UV curing</td>
<td>22</td>
</tr>
<tr>
<td>13</td>
<td>The EL materials used for each mask design</td>
<td>25</td>
</tr>
<tr>
<td>14</td>
<td>Depositing ink onto mask</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>PEDOT layer on plastic substrate</td>
<td>27</td>
</tr>
<tr>
<td>16</td>
<td>Baking</td>
<td>28</td>
</tr>
<tr>
<td>17</td>
<td>Flowchart of a typical fabrication</td>
<td>30</td>
</tr>
<tr>
<td>18</td>
<td>Test Structure #1</td>
<td>33</td>
</tr>
<tr>
<td>19</td>
<td>Test Structure Pixel</td>
<td>33</td>
</tr>
<tr>
<td>20</td>
<td>Image of the actual test structure</td>
<td>34</td>
</tr>
<tr>
<td>21</td>
<td>Mask design of Test Structure #2</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure 22. Pixel layering for Test Structure #2 ................................................................. 37
Figure 24. Mask design for a 16x16 display ................................................................. 39
Figure 25. Layering of 16x16 display #1 ................................................................. 39
Figure 26. Mask Design #2 for the 16x16 display ..................................................... 41
Figure 27. Mask Design #2 for the 16x16 display ..................................................... 41
Figure 28. Mask Design #2 for a 32x32 display ....................................................... 44
Figure 29. Cascade of mask design #2 for 32x32 display ........................................ 44
Figure 30. Actual image of the 2nd 32x32 display ..................................................... 45
Figure 31. Apparatus used to measure the power output and current .................. 52
Figure 32. ThorLabs software ..................................................................................... 52
Figure 33. 3D plot of measurements taken .......................................................... 54
Chapter 1 – The FOELD Project

1. Introduction

The Flexible Organic ElectroLuminescent Display (FOELD) is a novel approach to the conventional LED and LCD display technologies. The project group consists of Cem Bonfil, Kevin Graff, Richard Beare, Thai Nguyen, Marc Ibrahim, Marija Vreco and Joshua D'Souza. The project was supervised by Professor Tom Smy and Professor Steve McGarry. The main objective of this project was to build a working 32x32 passive matrix display which has low power, high luminosity and high resolution.

This report will explain the FOELD technology, including the fabrication process, the physics involved and the sustainable benefits it offers. The technical aspect of engineering this display will be dealt with in full detail. The fabrication process and parameter extraction in developing the FOELD will be the main focus of this report.

The main topics of this report are as follows:

1. Organic Materials and Luminescence
2. Safety Requirements
3. Fabrication Process
4. Parameter Extraction
5. Optimization
6. Sustainability
2. Objective

2.1. Passive 32x32 Matrix Display

The main objective of this project was to build working display layout which would function to the controls and specifications defined by the microcontroller team. This included designing various layouts for the display, in order to find an optimum device, as well as picking out favourable variables to ensure high definition. A passive matrix is simply implemented using \([m, n]\) addressing. The 32x32 display gives a fairly high resolution of 512 pixels per inch (PPI), considering the screen-printing method. The display needs to be self-illuminating, and be able to run on a small AC voltage. It should also be relatively easy to manufacture.

2.2. Parameter Extraction

This task involved carefully extrapolating data for luminosity, lifetime and current of each pixel with varying frequency, which would then be used to help define a model for the display structure.

2.3. Project Management

As Project Manager, tasks were assigned to various members of the project, including deliverables and deadlines, based on their individual course load. Group and sub-group meetings were also scheduled to ensure integration and an open environment for ideas and suggestions.
3. Motivation

3.1. Current Display Technology

The market for flat panel displays (FPDs) is estimated to be worth at least $70 billion (1). Since 2000, with the reduced cost for manufacturing and improvements over the standard cathode-ray tube displays (CRTs), Liquid Crystal Displays (LCDs) have dominated the FPD market, being used not only as monitors, but also for mobile phones, portable media players and GPS systems. Because of their increasingly small size, the practical implementations are countless.

However, a recent trend has grown towards using light-emitting diodes (LEDs) to replace the current LCD market. They were first put into use as backlight for FPDs and are environmentally friendly (2). Studies have shown that the cost for LCD displays is still relatively high and the manufacturing process is much more complicated. They also use inorganic materials making it less environmentally friendly by comparison.

Recently, there is a dominance of organic LEDs (OLEDs) in the display market (3). OLEDs have the distinct advantage over LCDs and OLEDs in that they are:

1. Self-emitting with higher resolution, flexibility and luminosity (4);

2. Capable of better colour reproduction with better power efficiency (5);
3. Cheaper to manufacture

This leads to the following consequent advantages. Because of their self-luminance, OELDs use less power and offer higher contrast ratio. This in turn leads them to function better since they do not over heat as much. EL also can be printed using screen-printing or inkjet-printing to layer each material. This makes the considerable cheap and easy to manufacture.

They can be developed as micro displays (6)- (7), with pixels of the order of about 12µm, or even as regular large-scale displays. However, they can suffer from lifetime issues.

3.2. Feasibility as a replacement for paper

Over the last 3 years, electronic books (eBooks) have made its way into the paper publishing business. A multiple eBooks can be loaded on an eBook reader, allowing a potentially large and portable library. So far, electronic ink (E-Ink) has been used for several of these eBook Readers (8)- (9), which is not organic. With their low cost and environmental superiority, OELDs would make a great substitute in this market. In addition to this, OELDs can be printed on substrates that are paper-thin. They do, however, require a power source, with a good amount of driving voltage (but low current).
3.3. **Sustainability of Organic Materials**

The need for a sustainable and more environmentally friendly solution for displays is now becoming more prevalent as computer technology becomes a staple to society. Manufacturing LCDs result in emission of nitrogen trifluoride, which is considered to be one of the greenhouse gases (10). Successfully built OLEDs, being thin and low power, are capable of replacing books and newspapers completely, and are much less toxic to the earth.
Chapter 2 – Professional Practice

1. Health and Safety

1.1. WHMIS

The fabrication aspect of this project required special attention and care when working with the specific chemicals. All fabrication members were required to adhere to Workplace Hazardous Materials Information Safety (WHMIS) regulations. The MSDS information for all of the materials used is listed in the appendix.

1.2. Health and Safety

The following is a breakdown of some of the safety precautions taken while fabricating the masks and screens:

• Gloves – some of the materials and solvents, specifically Acetone, used were corrosive and could penetrate through the skin, and cause irritation and skin burns.

• Lab coat – similar to the gloves, the lab coat provided extra protection for open areas of the body, like the upper arms.

• Goggles – this was used to protect our eyes from the laser beam. This high-intensity beam was capable of burning the retina.

In addition to this, there was a considerable amount of glassware being handled. This required special care, and in the event of a spill, it was reported to our supervisor. Because of the heavy course load, there was a significant amount of work that was carried out in the fabrication lab.
alone. However, this was only restricted to tasks that would not result in a likely and potentially dangerous accident. Unattended work was also kept to a minimum, and included only the screen writing (lasering) and oven preheating. Screen writing was checked on at least once every hour (with the process taking about 2 hours), and preheating was checked every 20 minutes (the oven would take approximately 40 minutes to reach the desired temperature).

2. Engineering Professionalism

As project manager, there was a huge responsibility in making sure that tasks were carried out in a professional manner, and group members and their concerns were handled with objectivity and sound ethical judgment. Negligence and accountability were of significance especially when working in the fabrication lab. All accounts of such behaviour were reported to the supervisor.

All members were treated in the same respect, regardless of differences in appearance or philosophy. This helped embody a sense of equality between all of us. If tasks were not carried out as expected, it was dealt with complete honesty and professionalism.

As professional engineers, the preparation for each task involved looking up resources and relevant information that would help us. This included journals, published papers as well as online citations. This allowed us to equip ourselves with the necessary knowledge to undertake any tasks.
3. **Project Management**

The main task in working in a group environment was to ensure that all the strengths of individual members were brought out, and amalgamated so that the team itself functioned efficiently. This was done simply by asking the members what it was that motivated them and how their skills could be assigned to reach the objective, and then using that to assign tasks. Quite often, there was a good share of conflict, but in order to complete the project, that was handled delicately, so as not to allow the project or its members to suffer.

One of the methods used to keep the project going in good spirit was to keep its members happy through compromise. While this is far from what has been thought in engineering courses, a similar business plan was incorporated by Johnson & Johnson showing great results (11). Tasks were assigned so as not to elevate stress levels but instead to balance out the mental and physical fatigue. In addition to this, extra-curricular group activities were also encouraged.

Any lack of work or redundancy of the team was made up for personally. Each week, the subgroups were required to meet with their supervisors to review their current status, and to go over the plan for progress. A Gaant chart was made up in September (see Appendix B). This chart gave an idealistic schedule for each member.
At each bi-weekly group meeting, tasks were assigned based on the progress made. All subgroups worked interdependently, so subgroup’s task would have a direct impact on another subgroup’s task. This allowed work to flow more fluidly, since results were expected every two weeks. The following chart gives an account of what was achieved by each member.

![Month-by-Month Progress Chart]

*Figure 1. Month-by-Month Progress of each team member.* Due to the heavy workload, these tasks were a much more streamlined version of what was initially assigned in the original Gaant chart (see Appendix).
1. How OELDs Work

The display that will be built will be multi-layer OLED using electroluminescence. Typically this involves using a transparent ionomer cathode, an insulator layer, an emissive phosphor layer and a transparent ionomer anode, with metal contacts. The anode could also possibly be silver, aluminium or calcium. These are layered on a substrate, usually glass or any other non-conductive substrate. The figure below shows a cross-section of a typical OLED:

As an alternating current (AC) is applied to the device, electrons are accelerated to the point where they are able to transfer to the phosphor atoms, emitting light. This is also known as high-field electroluminescence (12)- (13). The inorganic-hybrid phosphor layer

![Figure 2. A typical single-layer electroluminescent display on substrate. The dielectric layer need not be transparent in this case.](image-url)
has more mobile holes, allowing for a higher probability for electron-atom interaction.

The dielectric layer acts as an insulator, ensuring that only electrons with high energy are being accelerated into the phosphor region, and leading to luminescence. The electron, upon interaction with an atom, excites the electron to a higher energy state. If this energy is high enough (between 2-3eV), photons are visible.

The phosphor layer emits a fluorescent light, with a tint of blue, red or green. The composition of the phosphor region can change the colour of the emitted light. The frequency of the AC signal is directly correlated to the excitation states, which in turn leads to varying colour in the photon emission.
2. Electrical Model of OELD pixel

OELDs function similar to a circuit of a series connection of a resistor, and a resistor, tunnelling diode and a capacitor in parallel (see Figure 4). The resistor in series represents resistance of the contacts. The parallel circuit defines the phosphor and dielectric layers. The tunnelling diode only allows forward bias operation.

![Theoretical model of the EL display. The resistor-capacitor parallel pair depicts the dielectric and phosphor regions.](image)

3. Passive and Active Matrix Addressing

Most OLED displays in production today use a passive-matrix (PM) type screen, but are usually used in low-density applications. This method involves using line scanning, where the anode and the cathode use addressing to light up a specific pixel (14). Figure 5a shows a simple layout of how the addressing sends a current through the selected pixels. The problem with PM type OLEDs is that they have higher power dissipation, and cannot be used for high-resolution TVs and monitors which require a high frequency scan time. However, for smaller
displays, they are quite suitable due to their ease of implementation (15). An active-matrix type addressing offer lower power dissipation and also improves the overall lifetime of the display, and also allows for higher density PPI. Using ‘pixel-memory’, the current is stored in a pixel capacitor, keeping the brightness, and keeping the current DC (see Figure 5b).

![Figure 5. PM-OLED and AM-OLED.](image)

(a) The left image shows PM addressing, which uses a simple line-scanning to light up a pixel. (b) The right image shows AM addressing, which stores current in a capacitor, keeping the pixel lit[9].

However, due to the complexity involved, AM-OLEDs are not the preferred type of addressing used.
Chapter 4 – Building the Mask

1. Designing the Test Structures

1.1. Software

Adobe Photoshop CS4 was used to design the first set of test structures. Photoshop offers a layer by layer designing, which was ideal for masks. Each layer could be made partially transparent, making layer and aligning much easier. Once the design was finished, the file was imported into Jasc Paint Shop Pro. Each layer was separated and converted to a .pbm file, which could be used with the laser software. Each of the mask designs had a size of 2500x2500 pixels, which related to 2500x2500 mils². The active mask design area was limited to 2200x2200 pixels.

1.2. Test Structure #1

The following designs were used to test to find an appropriate size for each of the pixels for the final display (see Figure 6 and Figure 7). All remaining test structures were designed by K. Graff.
Figure 6. Test Structure #1. This test structure was made of three layers, in order: PEDOT (cyan), Dielectric (red) and phosphor (yellow). The purpose of this test structure was to find the smallest pixel with good resolution.

Figure 7. Text Structure Pixel. This shows a typical pixel layer, which shows the relative size. The dielectric layer has a 5 mils border more than the other two layers.
2. Mask Fabrication Process

2.1. Software – HP VEE

The screen-writing (lasering) software was designed in HP Vee by Prof. McGarry for some of his earlier projects. The software ran a signal to the laser turning it on, meshing the emulsion, or off to allow the emulsion to be washed away. While the exact details of the software are vague, some of the parameters were adjusted to allow for better lasering:

- **Lasering Time** – this defined the amount of time the laser was at a specific position. This was particularly helpful during some of the latter trials.

- **Laser Intensity** – this was used to adjust the level of the laser. A higher intensity beam would mesh the emulsion better to the screen.

The software required that each of the pbm files were of 2500x2500 pixels in size, which was the threshold of the lasering area.
2.2. Emulsion and Screen

The emulsion used for fabrication was the Diazo Emulsions. These are the most popular emulsions used for screen printing. The emulsions are water soluble, and wash off easily. They are UV sensitive and change colour when the emulsion has cured. The curing process involves cross-linking and sensitizing. As the emulsion is exposed to UV light, the sensitizer catalyzes the emulsion resulting in an interlocking of molecular chains, making them insoluble in water.

All of the emulsion processing was done with no white light. Sodium lamps were used as safety lights. Using gloves, the emulsion roll was cut up into 6”x6” squares. Using a clean prepped screen, deionised water
was sprayed onto both sides of it. The emulsion square was carefully placed on the screen, shiny side up. A squeegee was used on the front to ensure that the emulsion was firmly stuck to the screen and to prevent any air bubbles. Deionised water was sprayed onto the back, and was squeegeed (see Figure 9). A good screen would have slightly coloured water drip off.

![Figure 9. Screen Preparation.](image)

Once this was done, the screen was placed in a dark drawer, and a sheet of black cardboard was placed over it, along with a sheet of static-free water absorbent napkin. After drying overnight, the thin plastic film from the emulsion was removed, and the screen was left to dry for a few
more hours. Once this was done, the screen was ready for lasering (screen-writing).

2.3. Screen Writing

The laser used was developed and manufactured by Power Technology Inc in the USA (see Figure 10). The PPMT25/5231 laser was a 405nm GaN (Gallium-Nitride) diode laser. Dr. McGarry had been using this setup for at least 5 years, prior, so no additional assembly was required.

![Figure 10. The PPMT25/5231 Laser. This 405nm laser was powered using an external power supply (not shown). Using a serial interface, it was connected to the computer which ran the HP Vee software. This laser, because of its high-intensity beam, required goggles when being operated (unless covered).](image)

The amplitude of the current driving it was set to approximately 12A. The first a dummy screen was loaded on the holder. A sample Square Test was run on HP Vee. This was done to ensure uniformity with the
laser. Once this was done, with all white light sources turned off, the actual screen was loaded and covered by a black cloth, and the pbm was loaded. As the laser ran through each horizontal line of the mask, a counter was triggered on the software. Once this reached 2499, lasering was complete. The lasered area of the screen showed a slight discoloration compared to the rest of the screen.

2.4. UV Exposure
With the white lights still off, the screen was removed from the laser mount. At a certain angle, the lasered area could be seen. A metal blocker was placed over this region and under it as well. A magnet was used to keep the two blockers from shifting. This was placed under a high powered UV lamp for an hour on each side (Figure 11).
Figure 11. **UV Exposure and emulsion curing.** Once the mask was written on to the emulsion, the region was blocked off, and the rest of the screen was cured using a high powered UV lamp. Once this was complete, the screen was washed, and placed for additional exposure.

Once properly exposed, the reflection of the UV light was considerably lower than at its start.

2.5. **Washing**

Once the screen was sufficiently exposed to UV light, the screen was washed. Using lukewarm water, the stream was set to hit the screen just near the top of the lased section. The water was also made to run in the optimal direction of the mask design, that is, the screen was rotated so that the flow of water did not go against the emulsion, but with it. Little to no foreign interaction, like rubbing out the emulsion, was used to ensure the edges were well defined. Once this was complete, the
screen was placed under the UV lamp for 30 minutes on each side (Figure 12).

Figure 12. Post-wash UV curing. The screen was washed, and placed for additional exposure.

3. Designing the Test Display

3.1. 16x16 vs. 32x32

Initially a 16x16 display was set as the objective. However, due to the poor resolution, a 32x32 display was considered. However, due to problems faced in screen fabrication (discussed later), this was practically impossible. Over a month of iterating different ratios for conductor lines and gaps, and eliminating individually defined
phosphor pixels, a 32x32 screen was producible. The following table shows the ratios tested and their results:

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>Spacing between pixels</th>
<th>Ratio (pixel: spacing)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>5</td>
<td>9:1</td>
<td>Emulsion peeled off</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>4:1</td>
<td>Emulsion peeled off</td>
</tr>
<tr>
<td>35</td>
<td>15</td>
<td>7:3</td>
<td>Emulsion peeled off in some places</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>3:2</td>
<td>Good resolution</td>
</tr>
</tbody>
</table>

Table 1. Pixel Size selection for a 32x32 display. Each of the pixel sizing was tried and tested to see if the resolution was acceptable.

3.2. Mask Design

Working with R. Beare, a finalized display was agreed upon. Using the specifications of his PCB layout, the mask layers were designed appropriately. Table 2 shows the specifications of the mask to match the PCB layout.

<table>
<thead>
<tr>
<th>Mask size</th>
<th>32x32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display size</td>
<td>2.51 inch(^2) (1.585”x1.585”)</td>
</tr>
<tr>
<td>Pitch (conductor pads)</td>
<td>0.100”</td>
</tr>
<tr>
<td>Display size (with conductor pads)</td>
<td>4.41 inch(^2) (2.1”x2.1”)</td>
</tr>
</tbody>
</table>

Table 2. Pixel Size selection for a 32x32 display. Each of the pixel sizing was tried and tested to see if the resolution was acceptable.

3.3. Layering

During iterations, several methods were tried to obtain a dual-sided screen. These included using only PEDOT for the cathode and anode, and only silver for the contacts. Another idea was to use a clear dielectric layer in conjunction with the previous PEDOT cathode-anode
combination. Finally a bleaching process was tested so that the substrate itself could function as the cathode.

However, based on the PCB layout, having a two sided screen was not attainable. With some suggestions from Beare and Prof. McGarry, it was agreed to cut a square hole through the PCB, in the region of light emission.

After designing the mask, it was overviewed by C. Bonfil so that he would be able to extract any relevant data from it to base his model on.

4. Test Structure and Display Printing Process

4.1. Materials Used – Phosphor, Dielectric, Silver, PEDOT

The final display was constructed on both glass and on plastic substrate. The following is a list of the materials used (datasheets and MSDS information is shown in the appendix):

- **Orgacon™ EL-P 3040** was used as the transparent conductive screen-printing ink. The active chemical used is PEDOT:PSS (Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate)). The ink had a recommended dry-time of 2-3 minutes at 130°C. It was also water soluble.

- **DuPont 5036** was used as the thermal dielectric. This polymeric colourless ink had rapid-curing and a recommended dry-time of 5 minutes at 125°C. Only partially water-soluble, it required clean-up
solvents to remove residue. It was also recommended that two layers of dielectric be used.

- **DuPont 8152/8152B** was used for the phosphor layer. 8152B was the predominantly used ink, due to its higher brightness. And moisture protection. It had a typical dry-time of 10 minutes at 130°C. This cream coloured paste glows blue-green when powered. It required special clean-up solvents to remove any residue from the screens.

- **ERCON E1660-136** was used as the conductor layer. This paste consisted of fine silver particles in a resin. The ink required at least 15 minutes of dry-time at 125°C. It also required special clean-up solvents to remove residue.

![Figure 13. The EL materials used for each mask design. From left to right: Phosphor (DuPont Luxprint 8152B), Dielectric (DuPont 5036), Silver (Ercon E1660-136) and PEDOT (Orgacon EL-P 3040).](image)
4.2. **Screen Printing**

The method to print out each of the layers was done using screen-printing. This is similar to what they use for printing out t-shirts. A glass slide was place on the holder and aligned with three screws. Once aligned, the glass slide was held in position using a vacuum pump. The desired mask was placed over the slide.

The desired material was deposited along the top of the mask design using a spatula (Figure 14). Using the squeegee, in a fast motion, the ink was pressed across the design and through the mask. The mask was removed, and the vacuum was turned off. The glass slide was removed and placed in the oven. Any additional slides were printed on using the same mask in the same manner.
Figure 14. Depositing ink onto mask. The mask was placed over the substrate. Ink was deposited using a spatula. The ink was then deposited onto the substrate with the screen-printer.

Figure 15. PEDOT layer on plastic substrate (taped on glass slide). This is what the ink deposition looks like after screen printing.
4.3. **Baking**

The vacuum oven was preheated to 125°C for about 40 minutes before placing any slides inside. After each layer was deposited, the glass slide was placed inside the oven for approximately 15 minutes (Figure 16). The slide was then removed and the subsequent layer was printed on, and the process was repeated.

As an additional processing step (which was introduced halfway through the overall project), all the slides were heated in the oven for about 10 minutes before being initially printed on.

*Figure 16. Baking.* The test displays are being baked in a vacuum oven at 125°C for 15 minutes, to allow the ink or paste to dry.
4.4. Screen Care

After each layer was printed onto the glass slides, the screen was then washed. This was done in a number of ways. The PEDOT screen was washed off only with water, since it was soluble. The other screens required a screen wash. An anti-static wipe was soaked in the screen wash, and was used to wipe off the excess ink from the screen, on both sides.

Once the screens were done being used, the emulsion was stripped off using an emulsion remover. A soft-bristle toothbrush was soaked in the remover and used to gently rub off the emulsion. The screen was then washed off with running water.

If there was any remaining residue, acetone was used on the screen to remove it with a toothbrush, and subsequently washed off with water. The screen was then allowed to dry for a little bit and examined for residue. If any, it was rubbed off with either acetone or the screen wash.
Figure 17. Flowchart of a typical fabrication process undertaken to build a display or test structure. The flowchart does not include unexpected problems, like bending or residue build-up.
Chapter 5 – Testing & Results

1. Testing the Display

1.1. Equipment Set up & Apparatus

A completely layered OELD was tested for functionality using the following instruments:

- **HP 331208 Function Generator** – this was used to send an AC voltage into the circuit to drive the OELD. A square wave was found to have better luminosity. The benefit of this generator was that it had a digital interface, so it was easy to switch between different voltages and frequencies.

- **29-step transformer** – this was a simple audio step-up transformer used to step up the voltages up to the level to light up a pixel.

- **Breadboard** – this was used to mount the transformer and connect the leads to the generator and to the EL display.

- **Wires** – these were of various sizes and helped route the signal to the display.

- **Holder/Clamp** – this was used to hold the glass slide so that the pixel would be viewable. This was especially necessary for the single-sided display.

- **Tektronix TDS 3014 Oscilloscope** – this was used to measure the voltage and the signals before and during the testing. The
oscilloscope helped distinguish whether or not the transformer was burnt out.

1.2. Results

Each of the contact rows and columns were tested to see if the pixels lit up. All of the test structures and mask design results are shown in the next sections.

1.2.1. Test Structures #1

The test structures were designed to find the optimal pixel size. The range went from 10x10 mils to 200x200mils (Figures 18-20). The layers were stacked on a plastic substrate. The following table gives the characteristics of the test structures:

<table>
<thead>
<tr>
<th>Smallest pixel</th>
<th>10x10 mils²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Largest pixel</td>
<td>175x175 mils²</td>
</tr>
<tr>
<td>Smallest pixel with good illumination</td>
<td>50x50 mils²</td>
</tr>
<tr>
<td>Alignment</td>
<td>Layers were aligned fairly well over each other.</td>
</tr>
<tr>
<td>Substrate Type</td>
<td>Plastic (conductive)</td>
</tr>
<tr>
<td>Pixel stack</td>
<td>Phosphor → Dielectric → PEDOT</td>
</tr>
</tbody>
</table>

Table 3. Specifications for the first set of test structures. The smallest pixel with best illumination was found to be 50x50mils².
Figure 18. Test Structure #1. This test structure was made of three layers, in order: PEDOT (cyan), Dielectric (red) and phosphor (yellow). The purpose of this test structure was to find the smallest pixel with good resolution.

Figure 19. Test Structure Pixel. This shows a typical pixel layer, which shows the relative size. The dielectric layer has a 5 mil border more than the other two layers.
Figure 20. Image of the actual test structure. As can be seen, some of the outer pixels did not get completely aligned with the rest of the layers. There was also some bad resolution on the smaller pixels.
1.2.2. Test Structures #2

The test structures were designed specifically to find the best thickness for the conductor lines (Figures 21-23).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinnest conductor line</td>
<td>10 mils</td>
</tr>
<tr>
<td>Thickest conductor line</td>
<td>50 mils</td>
</tr>
<tr>
<td>Thinnest conductor line with good</td>
<td>30 mils</td>
</tr>
<tr>
<td>alignment/resolution</td>
<td></td>
</tr>
<tr>
<td>Smallest Pixel</td>
<td>10x10 mils$^2$</td>
</tr>
<tr>
<td>Largest Pixel</td>
<td>175x175 mils$^2$</td>
</tr>
<tr>
<td>Smallest pixel with good</td>
<td>30x30 mils$^2$</td>
</tr>
<tr>
<td>illumination</td>
<td></td>
</tr>
</tbody>
</table>

Alignment Layers were aligned fairly well over each other. Some misalignment with conductor layer for smaller pixels.

Substrate Type Plastic (conductive)

Pixel stack Phosphor $\rightarrow$ Dielectric $\rightarrow$ PEDOT

Table 4. Specifications for the first set of test structures. The smallest pixel with best illumination was found to be 30x30mils$^2$. 
Figure 21. Mask design of Test Structure #2. The purpose of the test structure was to find the thinnest conductor line. This was found to be 30 mils. The layering was as follows: Phosphor (yellow), Dielectric (red), PEDOT (blue).

Figure 22. Pixel layering for Test Structure #2. The layering was such that the conductor layer had a probe, with a thin line connecting it to the main pixel.
Figure 23. Actual image of test structure #2 under UV light. The PEDOT layer shows some distortion. Overall, the pixels seemed well defined.
1.2.3. **16x16 Mask Design #1**

This mask design was comprised of 80x80 mils\(^2\) pixels arranged in a 16x16 layout, giving a 256-bit resolution. Each of the pixels was defined, and had a multi-layer stack (Figure 24-25).

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>80x80 mils(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel-pixel spacing</td>
<td>20 mils</td>
</tr>
<tr>
<td>Pixel-space ratio</td>
<td>4:1</td>
</tr>
<tr>
<td>Conductor Thickness</td>
<td>90 mils</td>
</tr>
<tr>
<td>Conductor Pad size</td>
<td>150x150 mils(^2)</td>
</tr>
<tr>
<td>Screen size</td>
<td>1580x1580 mils(^2)</td>
</tr>
<tr>
<td>Total size of the display (including conductor pads)</td>
<td>1940x1940 mils(^2)</td>
</tr>
<tr>
<td>Alignment</td>
<td>Major misalignment between conductor lines and the phosphor pixels. Some overlap between conductor lines and dielectric layer. Slight bending towards the left.</td>
</tr>
<tr>
<td>Substrate Type</td>
<td>Glass</td>
</tr>
<tr>
<td>Layer Stack</td>
<td>PEDOT(\rightarrow)Phosphor(\rightarrow)Dielectric(\rightarrow)Silver</td>
</tr>
</tbody>
</table>

**Table 5. Characteristics of the first 16x16 display.** The first set of laser problems caused bending in the mask design.
Figure 24. Mask design for a 16x16 display. Top to bottom: PEDOT (blue), Phosphor (yellow), Dielectric (red) and Silver (Green).

Figure 25. Layering of 16x16 display #1. The individually defined phosphor pixels caused trouble with alignment.
1.2.4. 16x16 Mask Design #2

The idea for this mask design came from testing with C. Bonfil to study the effect of current spreading over a larger phosphor region. It was found that the current only travelled within the crossover of the anode and cathode. The phosphor region was changed to just a simple blanket layer, slightly smaller than the dielectric layer (Figure 26-27). This way, the alignment issues were fixed.

<table>
<thead>
<tr>
<th>Pixel Size</th>
<th>80x80 mils$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel-pixel spacing</td>
<td>20 mils</td>
</tr>
<tr>
<td>Pixel-space ratio</td>
<td>4:1</td>
</tr>
<tr>
<td>Conductor Thickness</td>
<td>90 mils</td>
</tr>
<tr>
<td>Conductor Pad size</td>
<td>150x150 mils$^2$</td>
</tr>
<tr>
<td>Screen size</td>
<td>1580x1580 mils$^2$</td>
</tr>
<tr>
<td>Total size of the display (including conductor pads)</td>
<td>1940x1940 mils$^2$</td>
</tr>
<tr>
<td>Alignment</td>
<td>Slight bending towards the left.</td>
</tr>
<tr>
<td>Substrate Type</td>
<td>Glass</td>
</tr>
<tr>
<td>Layer Stack</td>
<td>PEDOT$\rightarrow$Phosphor$\rightarrow$Dielectric$\rightarrow$Silver</td>
</tr>
</tbody>
</table>

*Table 6. Characteristics of the second 16x16 display.* The phosphor region is now a simple blanket layer.
Figure 26. Mask Design #2 for the 16x16 display. The layer is as follows: PEDOT (blue), Phosphor (yellow), dielectric (red) and Silver (Green).

Figure 27. Mask Design #2 for the 16x16 display. From the layering, it can be seen that there is little room for misalignment using a blanket phosphor layer.
1.2.5. **32x32 Mask Design #1**

This mask design involved using an inverse mask for the first conductor layer so as to bleach the substrate. The conductive plastic substrate was to be bleached everywhere except where the conductor lines ran.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>30x30 mils²</td>
</tr>
<tr>
<td>Pixel-pixel spacing</td>
<td>20 mils</td>
</tr>
<tr>
<td>Pixel-space ratio</td>
<td>3:2</td>
</tr>
<tr>
<td>Conductor Thickness</td>
<td>30 mils</td>
</tr>
<tr>
<td>Conductor Pad size</td>
<td>80x80 mils²</td>
</tr>
<tr>
<td>Screen size</td>
<td>1585x1585 mils²</td>
</tr>
<tr>
<td>Total size of the display</td>
<td>2000x2000 mils²</td>
</tr>
<tr>
<td>Alignment</td>
<td>Slight bending towards the left. Bleaching spread, leaving no well defined conductor lines.</td>
</tr>
<tr>
<td>Substrate Type</td>
<td>Conductive Substrate</td>
</tr>
<tr>
<td>Layer Stack</td>
<td>Bleach → Phosphor → Dielectric → Silver</td>
</tr>
</tbody>
</table>

*Table 7. Specifications and characteristics of the first 32x32 mask design. This was a single-sided display.*
1.2.6. **32x32 Mask Design #2**

This was the final 32x32 design, based on the PCB specifications given by R. Beare. Each of the contact pads had a 100 mil pitch (Figure 28-30).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>30x30 mils²</td>
</tr>
<tr>
<td>Pixel-pixel spacing</td>
<td>20 mils</td>
</tr>
<tr>
<td>Pixel-space ratio</td>
<td>3:2</td>
</tr>
<tr>
<td>Conductor Thickness</td>
<td>30 mils</td>
</tr>
<tr>
<td>Conductor Pad size</td>
<td>200x70 mils²</td>
</tr>
<tr>
<td>Conductor Pad Pitch</td>
<td>100 mils</td>
</tr>
<tr>
<td>Screen size</td>
<td>1585x1585 mils²</td>
</tr>
<tr>
<td>Total size of the display</td>
<td>2100x2100 mils²</td>
</tr>
<tr>
<td>Alignment</td>
<td>Slight bending towards the left. Bleaching spread, leaving no well defined conductor lines.</td>
</tr>
<tr>
<td>Substrate Type</td>
<td>Glass/Plastic Substrate</td>
</tr>
<tr>
<td>Layer Stack</td>
<td>PEDOT → Phosphor → Dielectric → Silver → Dielectric → Phosphor → PEDOT</td>
</tr>
</tbody>
</table>

Table 8. Specifications and mask design for the second 32x32 display. This was designed with close attention to the detailed specifications of the PCB, given by R. Beare.
Figure 28. Mask Design #2 for a 32x32 display. The layering is as follows: PEDOT (Green), Phosphor (yellow), Dielectric (red), Silver (cyan), dielectric (red), phosphor (yellow) and PEDOT (green).

Figure 29. Cascade of mask design #2 for 32x32 display. The silver (grey) layer is sandwiched in between the other layers, allowing for dual sided display.
Figure 30. Actual image of the 2nd 32x32 display. Minus a few misalignment issues, this design turned out to have the best resolution and there were no extremely noticeable flaws.
Chapter 6 – Problems and Solutions

This section deals with some of the problems faced while fabricating the various test structures and displays. Most of the setbacks were due to the laser not scribing the emulsion well-enough or due to alignment.

1. Problems

1.1. Poor Resolution

The initial test structures showed that attaining a 30x30 mils\(^2\) pixel would be attainable. However, when this was tried, it was difficult getting all pixels to have good well-defined resolution. This also applied to the conductor lines. The spacing between any two washout regions had to be at least 20 mils. Another reason for poor resolution was that the emulsion wasn’t stuck to the screen well. A final plausibility for poor resolution was that the laser didn’t scribe the section well, making it harder to wash off. This in turn, caused peeling in the surrounding emulsion.

1.2. Bending

As more masks were being developed, it was found that a certain side would have some distortion in its shape. This was extremely prevalent in the blanket phosphor and dielectric regions. The only reason for this was due to thermal expansion of the laser.
1.3. Uneven ink deposits

After each batch of screen-printing, the masks needed to be cleaned thoroughly to prevent residual build-up. The PEDOT masks were easier to clean since the PEDOT was water soluble. The phosphor mask was also relatively easier to clean out. The problem with the silver was that it would collect around the edges, and could only be cleaned out from the front of the screen. In order to prevent damage to the mask design, these regions were dabbed with a wipe soaked in screen wash. The clear dielectric was sticky, and needed a little more force to clean out. Any residue would cause uneven ink deposition. Another plausible reason for this problem would be that the inks being used were expired.

1.4. Emulsion peeling

This was caused mostly due to improper adhesion to the screen. On occasion, the emulsion also peeled while cleaning the screen of inks, particularly when using acetone.

1.5. Misalignment of UV blockers

This was responsible for some misalignment, especially when collaborating with the electronics team. Once scribed, the UV blockers had to be placed over the design region. This region could only be seen at a certain angle in non-UV light, and thus there was always a huge room for misalignment.
1.6. **Misalignment of mask design**

Towards the end of the fabrication process of the final display, there was considerable misalignment between each layer. This was possibly due to the thermal expansion of the laser as it ran for longer hours. Another explanation would be that the screen wasn’t placed on its holder, although this seems unlikely.

2. **TABLE OF PROBLEMS & SOLUTIONS**

This section outlines the solutions to some of the problems faced.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor Resolution</td>
<td>• Emulsion adhered carefully and left to dry overnight</td>
</tr>
<tr>
<td></td>
<td>• Screen-prep used before placing emulsion on</td>
</tr>
<tr>
<td></td>
<td>• Laser strength set higher and for a slightly longer time</td>
</tr>
<tr>
<td>Bending</td>
<td>• Laser left to warm up for about 2-3 hours</td>
</tr>
<tr>
<td></td>
<td>• Square-test run to ensure uniformity before each scribing</td>
</tr>
<tr>
<td>Uneven ink deposits</td>
<td>• Screens cleaned carefully with screen wash</td>
</tr>
<tr>
<td></td>
<td>• Additional cleaning with acetone and a soft brush</td>
</tr>
<tr>
<td></td>
<td>• High-pressure air used to dry out the mask region</td>
</tr>
<tr>
<td></td>
<td>• Use ‘fresh’ inks and pastes</td>
</tr>
<tr>
<td>Misalignment of UV Blockers</td>
<td>• Active mask region was kept down to 2100x2100 mils²</td>
</tr>
<tr>
<td></td>
<td>• Better care while placing blockers to ensure it covered the region well</td>
</tr>
<tr>
<td>Misalignment of mask layers</td>
<td>• All mask layers were batched scribed, one after the other, on the same day within 12 hours</td>
</tr>
</tbody>
</table>

*Table 9. Problems faced during fabrication. The solutions were actual tasks undertaken.*
Chapter 7 – Improving the Display

1. Improving the Display

1.1. Different Materials (BLEACH), Clear Dielectric, Silver

Different inks were used to achieve optimal luminosity. Amongst these are the ones listed below, with an explanation as to why they were chosen or disregarded.

- **Bleach** – In order to reduce the resistivity of the pixel, it was decided to bypass the PEDOT layer and instead use a conductive substrate instead. The process would use an inverse mask design. The bleach, mixed with Strupas, would then, upon deposition, break the polymer bonds on the substrate, making that region non-conductive. This process was tried twice, but due to poor resolution of the deposits, was scrapped.

- **Clear Dielectric** – a clear dielectric was chosen as the optimal dielectric layer because a dual-sided display was expected. The other dielectric inks were opaque and required at least 2 layers of deposition; this reduced the overall brightness of the pixel. The clear dielectric also made it easier to manually resolve any misalignment between layers.

- **Silver** – The initial design called for both conductor lines to be PEDOT, with silver conductor pads. However, on testing, this was found to let less current in that anticipated. Thus, silver was
used as the top conductor line (for the single-sided display) and as the sandwiched conductor line (for the dual-sided display).

- **Glass** – Glass allowed for less misalignment for each of the subsequent layers as they were being printed. The plastic substrates, while baking, would lift off the glass (due to thermal expansion), and lift some of the Kapton tape. This would cause the substrate to move slightly.
Chapter 8 – Parameter Extraction & Measurements

1. Equipment Used – Photometer, Software

1.1. Setup

The apparatus used to get measurements is the same as the testing apparatus (Figure 31), with the following additions:

- **ThorLABS S130C Power Meter** – this was a photodiode detector that measured the light through the detection window. It captured the light output in watts, and connected via USB to a computer which recorded its readings. The software was adjusted to work relative to the require wavelength range (about 500nm) and take an average reading over 3 seconds (Figure 32). The detector had an uncertainty of about 3% in the range being used. The data could be exported to a .txt file.

- **Tektronix TDS 3014 Oscilloscope** – The measurement function of the oscilloscope was used to measure the voltage across the resistor, so as to find the current running through the device.
Figure 31. Apparatus used to measure the power output and current. The power output was measured using ThorLABS 130C and a piece of slotted black card (to isolate the pixel).

Figure 32. ThorLABS software. This software could be calibrated to take in average readings and to work at a particular frequency range.
1.2. Setting up graphs

Once all the data was measured, it was imported into MS Excel. The voltage across the resistor was used to find the current. A sample of the data is shown below using 145V driving voltage, using a frequency range of 5 kHz to 25 kHz:

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Pixel Power Output (nW)</th>
<th>Voltage (across resistor) (V)</th>
<th>Current (µA)</th>
<th>Electrical Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>12.14</td>
<td>0.21</td>
<td>170.54</td>
<td>24.73</td>
</tr>
<tr>
<td>6000</td>
<td>11.92</td>
<td>0.24</td>
<td>198.21</td>
<td>28.74</td>
</tr>
<tr>
<td>7000</td>
<td>12.68</td>
<td>0.28</td>
<td>223.21</td>
<td>32.37</td>
</tr>
<tr>
<td>8000</td>
<td>13.22</td>
<td>0.31</td>
<td>244.64</td>
<td>35.47</td>
</tr>
<tr>
<td>9000</td>
<td>14.07</td>
<td>0.33</td>
<td>266.07</td>
<td>38.58</td>
</tr>
<tr>
<td>10000</td>
<td>14.28</td>
<td>0.36</td>
<td>287.50</td>
<td>41.69</td>
</tr>
<tr>
<td>11000</td>
<td>15.48</td>
<td>0.38</td>
<td>310.71</td>
<td>45.05</td>
</tr>
<tr>
<td>12000</td>
<td>16.60</td>
<td>0.40</td>
<td>317.86</td>
<td>46.09</td>
</tr>
<tr>
<td>13000</td>
<td>18.70</td>
<td>0.41</td>
<td>337.50</td>
<td>48.94</td>
</tr>
<tr>
<td>14000</td>
<td>20.39</td>
<td>0.43</td>
<td>344.64</td>
<td>49.97</td>
</tr>
<tr>
<td>15000</td>
<td>21.78</td>
<td>0.44</td>
<td>358.93</td>
<td>52.04</td>
</tr>
<tr>
<td>16000</td>
<td>24.27</td>
<td>0.46</td>
<td>373.21</td>
<td>54.12</td>
</tr>
<tr>
<td>17000</td>
<td>26.82</td>
<td>0.47</td>
<td>378.57</td>
<td>54.89</td>
</tr>
<tr>
<td>18000</td>
<td>29.74</td>
<td>0.48</td>
<td>389.29</td>
<td>56.45</td>
</tr>
<tr>
<td>19000</td>
<td>32.89</td>
<td>0.49</td>
<td>394.64</td>
<td>57.22</td>
</tr>
<tr>
<td>20000</td>
<td>36.89</td>
<td>0.49</td>
<td>403.57</td>
<td>58.52</td>
</tr>
<tr>
<td>21000</td>
<td>41.69</td>
<td>0.50</td>
<td>412.50</td>
<td>59.81</td>
</tr>
<tr>
<td>22000</td>
<td>46.19</td>
<td>0.50</td>
<td>416.07</td>
<td>60.33</td>
</tr>
<tr>
<td>23000</td>
<td>51.89</td>
<td>0.51</td>
<td>423.21</td>
<td>61.37</td>
</tr>
<tr>
<td>24000</td>
<td>58.24</td>
<td>0.51</td>
<td>426.79</td>
<td>61.88</td>
</tr>
<tr>
<td>25000</td>
<td>65.76</td>
<td>0.52</td>
<td>432.14</td>
<td>62.66</td>
</tr>
</tbody>
</table>

Table 10. Sample data using 145V driving voltage. The frequency was ranged from 1 kHz to 40 kHz, but only 5 kHz to 25 kHz is shown.

Once all the data was ready, each variable of for all sets was loaded as a vector matrix into MATLAB. This gave four matrices – for current, frequency, driving voltage and luminosity. Using the 3D surface function
in MATLAB, all four matrices were plotted to give a 3D graph, shown below.

Figure 33. 3D plot of measurements taken. See appendix for high-definition image.

1.3. Picking out optimum frequency/voltage

Upon testing, it was found that there was a considerable amount of crosstalk due to the capacitive nature of the EL pixels. Due to time restraints and lack of knowledge, it was decided that a voltage be selected so that the effect of this cross-talk would be minimal. The crosstalk itself still required a solution. The following table compares the voltage with the observable crosstalk (on a scale of 1-10).
Based on these measurements, it was decided that a driving voltage of 100V be used for the final display, while solutions to fix the crosstalk were being implemented.
Chapter 9 - Conclusion

1. Discussion

Based on the work conducted over the last 8 months, it can be said that the FOELD project was a partial success. The final product was a 32x32 passive matrix display, printed on both glass and flexible plastic substrate, with partially functional driving circuitry. Fabricating the device turned out to be slightly more difficult than initially expected, but with some clever tactical decisions and improvisations, a good resolution display was achieved.

The optimal driving voltage was identified, to produce the highest luminosity, and the varying frequency showed a potentially viable simplification of the current RGB tri-pixel down to a dual-pixel combination. However, considering that the driving circuitry was not tested with the actual display, the project still needs some additional work, including testing and verification, as well as testing for bending and impact while being driven.

The project also needs to address the crosstalk issue faced, by possibly taking into consideration an active matrix.

Based on the parameters measured, an adequate model was found and simulated to have similar characteristics as the actual display. The display was also shown to have a power output of around 0.8W/inch², which is about 2-3 times more than a typical LCD pixel. This is a considerable
benefit to the display field since it obviously offers a much better brightness.

2. Future Work and Considerations

Due to limited time constraints, the full effects and characteristics of an EL display were not studied. For undergraduate students planning to take over from where FOELD left off, there are a number of studies and considerations open for analysis. Given more time, some of the things that would be looked into are as follows:

- **Active matrix addressing** – the passive matrix circuitry used, while simple and easy to implement, is less efficient compared to the active matrix addressing. Active matrix addressing would be a good place for students driven by electronics and PCB design, as well as for students interested in fabrication.

- **Crosstalk** – there are a number of papers dedicated to the crosstalk issue that was encountered. There are a number of solutions that could be implemented to solve this problem.

- **DC FOELD** – since portable devices use DC to run, it would be a good idea to study and possibly manufacture a working display using DC. If successful, it would be easier to implement into practical applications.

- **Parameter Extraction** – properties and characteristics of each of the EL layers can be found, and thus are used to optimize the display and to get a better simulation model.
• Inkjet Printing – unless better resolutions are achievable using the nylon masks, the next step for fabrication would be to move onto an inkjet printing method. This would allow much higher resolution, and possibly less likeliness of misalignment. This would also involve inks that are fresh.

3. Practical Implications
The most practical application for FOELD would be that of a simple display in portable devices, like cell phones and eBook readers. The light-weight and flexible characteristics allow it to also be implemented into other applications like digital watches and heart-meters. The practical applications are countless, and because of the cheap and easy manufacturing method, FOELD can make a huge different in the display field.

A fitting application for FOELD would also be streetlights and bus shelters, as well as advertisement boards, purely as lighting. If used in conjunction with solar panels, this would enable better handling of civil power consumption, by not only being renewable, but also being low power.

Another valuable industry that would benefit from FOELD would be the rescue and aide services. By implementing FOELD into their safety jackets, it would make identifying such workers much easier. The same idea can also be used by mining and deep sea diving workers.
References


Appendix A
Chemicals – Datasheets & MSDS Information

- Acetone Cleaner MSDS
- DuPont 5036 (Dielectric) Datasheet
- DuPont Luxprint 8152B (Phosphor) Datasheet
- Orgacon EL-P 3040 (PEDOT:PSS) and MSDS
- Orgacon STRUPAS Ink Datasheet
- Teknecal TEK-401 (Emulsion Remover) Datasheet and MSDS
- Teknecal TEK-404 (Screen Rejuvenator) Datasheet and MSDS
- Teknecal TEK-454 (Screen Wash) Datasheet and MSDS
- Universal Mesh Prep Datasheet and MSDS

*No available MSDS sheets were found for Ercon E1660-136 (silver), DuPont 5036, DuPont 8152B, or for Orgacon Strupas. The same precautions as the Orgacon EL-P 3040 were taken. The MSDS sheets are available in the 5190ME, Carleton University, Ottawa.*
Appendix B
Gaant Charts

- Proposed Schedule
- Month-by-month assessment for each team member
Proposed Schedule
### Month-by-month Assessment for each team member

<table>
<thead>
<tr>
<th>Month</th>
<th>R. Beare</th>
<th>C. Bonfil</th>
<th>J. DSouza</th>
<th>K. Graff</th>
<th>T. Nguyen</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>Research</td>
<td>Parameter Extraction</td>
<td>LED Test Structure</td>
<td>Display Layout</td>
<td>Coding Hardware Improvements</td>
</tr>
<tr>
<td>November</td>
<td>Research</td>
<td>Fabrication (Test Structures #1)</td>
<td>Fabrication (Test Structures #2)</td>
<td>Research; Fabrication (16x16 Design #1)</td>
<td>Fabrication (16x16 #2)</td>
</tr>
<tr>
<td>December</td>
<td>Research</td>
<td>Mask Design (Test Structures #1)</td>
<td>Mask Design (Test Structures #2)</td>
<td>Mask Design (16x16 Design #1)</td>
<td>Mask Design (16x16 Design #1)</td>
</tr>
<tr>
<td>January</td>
<td>Research</td>
<td>Select component</td>
<td>Build the test structure</td>
<td>Display Functionality</td>
<td>Research and study programming</td>
</tr>
<tr>
<td>February</td>
<td>Research</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>Research</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix C
Final 32x32 Mask Design and Finished Product

- PEDOT Layer
- Phosphor Layer
- Dielectric Layer
- Silver Layer
- Finished product #1
- Finished product #2
PEDOT Layer Mask Design
Phosphor Layer Mask Design
Dielectric Layer Mask Design
Silver Layer Mask Design
Finished Product #1
Finished Product #2
Appendix D
Measurements

- Current and Output Power Readings
Appendix E
Graphs

- Current Vs. Frequency
- Power Output Vs. Frequency
- Power Output Vs. Driving Voltage Vs. Frequency (with Current)
Current Vs. Frequency

- 87V
- 116V
- 145V
- 174V
- 203V
- 232V
- 261V
- 275.5V
- 290V

Frequency (Hz)
Power Output Vs. Driving Voltage Vs. Frequency (with Current)