Design and Production Aspects of an Electroluminescent Segment Display

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The purpose of this study was to get a better understanding of the different ways printed circuits could be constructed and then implemented into creative, visual designs for printed electroluminescent displays. A variety of circuit design variables, such as area and length, were tested that will help create solutions for printed electronics.

This study tested different variables of circuit design, such as length of silver traces and the size of the image area, to help optimize ways to build a printed circuit. Then, findings were implemented into a segmented graphic display in order to analyze innovative ways to utilize multiple displays in a small area. Results found that there are a variety of recommendations that can be considered when designing an electroluminescent segment display. However, future testing can be done to develop wiring the power supply to the design.

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Table of Contents

List of Figures

Chapter One - Introduction

Printed electronics is an emerging technology in the Graphic Communication industry leading to the creation of new, innovative products. Flexible, electrical circuits can be printed using functional inks and traditional printing methods, such as screen printing, gravure, and inkjet. Printed electronics are perfect for low performance applications, such as displays, labels, clothing, and batteries. In order to better understand the capabilities of printed electronics, many tests still need to be conducted to find optimal ink functionality. This study focuses on one type of printed electronic: an electroluminescent (EL) display.

Production and manufacturing techniques still need to be optimized for EL displays. Printed electroluminescent inks are much less power efficient than other traditional lighting materials. The shelf life of the product is variable, the power source is limited, and its precise capabilities are unknown. In order for printed ELs to be incorporated into the Graphic Communication industry, they must be able to achieve the same effect that traditionally printed graphics can with limited cost. Uniform ink surface smoothness, fine lines, and registration are key in determining the capability of printed electronics. By screen printing electroluminescent inks, the necessary ink characteristics are needed for the electric circuit to function properly. The necessary inks can be designed in various ways, each with varying results. This research sought to answer two questions: First, how does the size of the image area, the length of silver trace lines, and the width of the silver trace lines affect the functionality in printed electroluminescent displays, and second, how can the different circuit design variables be implemented into a functional segmented design?

Electroluminescent inks create thin flexible designs that emit light when stimulated

by an electrical current. Conductive, insulative, and semi-conductive layers surround an electroluminescent phosphor layer, so that when connected to an AC power source, the phosphor emits light. Electroluminescent designs are vibrant and eye-catching due to the emitted light, which makes them favorable in marketing applications. The ability to print an image that can be stimulated by an electrical current can be a cost efficient solution if manufactured properly. This technology could change the way consumer products are viewed, as well as drastically improve the consumer shopping experience. As a growing field, the parameters necessary for printed electronics are still being adapted. Previous research and experiments on the different variables of the screen printing process to optimally produce ELs have been quantified, however the design of the EL circuit has not. The significance of this research was to test the different variables of designing electroluminescent circuits to see the impact on performance. The experiment intends to build a foundation for additional projects on implementing printed electronics into practical design projects.

Printed electronics proves to be a growing field with lots of room for testing and innovation. The interest in this study was to get a better understanding of the different ways printed circuits can be constructed and then implemented into creative, visual designs. By performing the various tests on length, width, and area of electroluminescent inks, a better understanding of how to implement printed electronics into consumer goods was discovered.

Chapter Two - Literature Review

As an emerging technology, the development of printed electronics continues to be defined thanks to the combination of traditional printing processes and innovative thinking. The concept of printed electronics dates back to the early 1900s with Thomas Edison's idea of using conductive particles and polymer-based adhesive to build circuits [1]. It wasn't until the 1940s that many contributors developed ways to tie Edison's idea to traditional printing technologies. Recently, many companies have continued developing and refining the process of producing printed electronics and their capabilities. Finding ways to maximize production, utilize new materials, and improve efficiency are key concepts in the advancement of printed electronics[2]. There are multiple printing processes capable of producing printed circuits, including screen printing, which provides desirable characteristics for printing functional inks. Screen printing is the process of pushing a viscous liquid through a stretched mesh. The thread count and the diameter of the threads of the mesh affect how much ink is transferred to the substrate [3]. Screens with higher thread counts tend to hold more detail due to less ink films and are capable of producing the fine lines necessary for printed electronics. Once the proper screen is selected, it is coated with a photosensitive emulsion (or stencil) that blocks the non-printing area of the screen [4]. Then, the image is printed onto a transparency, which is

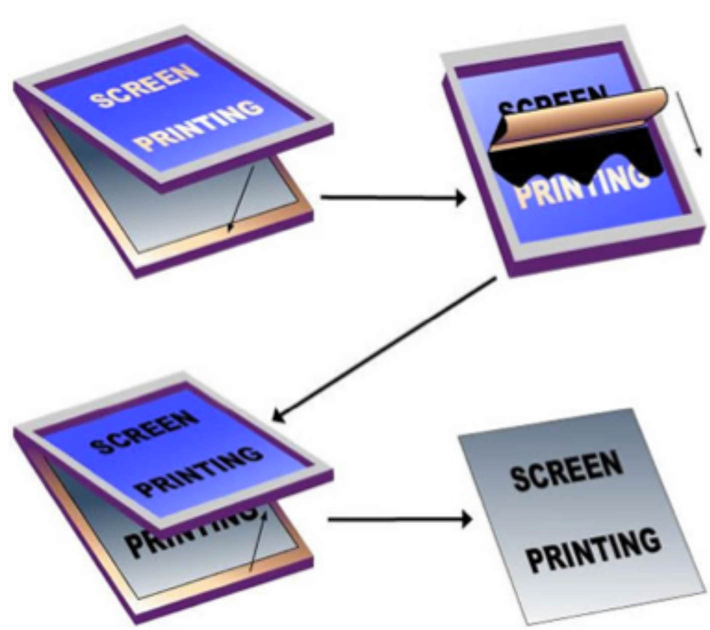

Figure 1— Screen Printing Process[11]

exposed onto the emulsion using ultraviolet light. Water is used to wash away the unexposed emulsion, leaving an area for ink to transfer through the mesh. After the screen is prepared, it is loaded into the printing press. Ink is placed onto one edge of the screen and a squeegee blade is used to push the ink through the mesh onto the substrate.

Screen printing provides many desirable characteristics necessary for printed electronics. Using screen printing is highly advantageous in the production of printed electronics due to its versatility and ease of use. One benefit of screen printing is the ability to create uniform ink films, however the process must be monitored closely to ensure the functionality of the inks [3]. Another advantage is the ability to print on a variety of substrates, such as the flexible films necessary for printed electronics. The ease of use and print characteristics makes screen printing a valuable resource for printed electronics.

Printed electronics is a growing field that combines traditional printing processes to produce electrical circuits. The use of functional insulators, semi-conductive, and conductive inks can be used to produce flexible circuits, solar cells, and displays. In 2009 the printed electronics market was worth $2 billion, with an expected growth of $60 billion in the next ten years, according to IDTechEx [2]. Printed electronics is an innovative and growing technology that requires more research and development. Although there are many applications, electroluminescent displays are particularly sought after for consumer products and displays. Electroluminescent (EL) displays produce a visible light by releasing photons by exciting a substance, like phosphor, and returning it to its ground state [5]. EL displays are used for applications such as background displays, control panels, and consumer packaging.

Materials used to build electroluminescent displays can be either organic or inorganic.

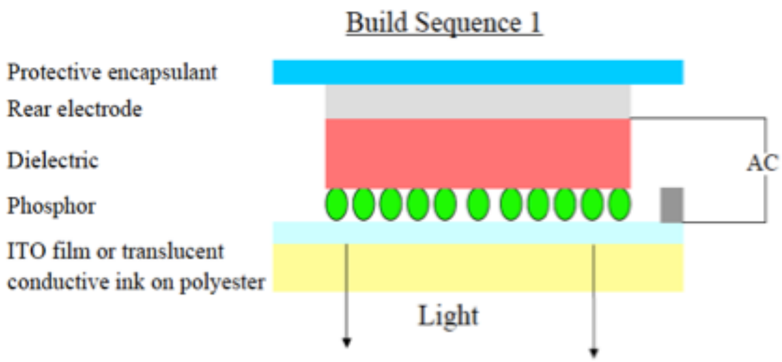

Figure 2 —Example Build Sequence of an EL Display[6]

The combination of different materials must be arranged properly for the printed circuit to function. EL displays consist of a layered structure with a front and rear conductive electrode with phosphor and dielectric layers in between [6]. When an electrical current is applied to the circuit, particles in the phosphor emit light. The front conductive electrode typically is composed of a transparent film coated with ITO (Indium Tin Oxide), which acts as the substrate. Functional inks that contain phosphor and dielectrics are then printed onto the ITO to complete the printed circuit. The dielectric acts as an insulator layer that is used to prevent arcing between conductive layers [5]. Specifically in screen printing, the functional inks must maintain certain viscosities and surface tensions to avoid problems, "such as drops that do not bond enough to conduct sufficiently, or an excessively rough surface that prevents the next functional layer from adhering" [7]. In order for the phosphor to emit light, either an alternative current (AC) or direct current (DC) can be applied. Lower voltages and frequencies are encouraged for longer life spans of the displays [8].

An understanding of circuits and electromagnetic waves is necessary for analyzing the performance of electroluminescent displays. Luminance is the intensity of light and can be measured per unit area using candelas per square meter. When a power source is applied to the printed circuit, the silver ink is charged with a negative potential, while the rear electrode is

charged with a positive potential. In between the positive and negative charges is the dielectric, an insulating material, and when sandwiched between the rear electrode and the conductive silver ink, it creates a displacement current [9]. A current is the flow of electrons from negative potential to positive potential, and the displacement current comes from the electromagnetic field generated by the difference in potentials between the silver ink, and rear electrode. This current continuously moves through the phosphor of the circuit, causing it to emit light [9]. The intensity of the luminescence is determined by how much displacement current can travel through the silver trace to interact with the phosphor. This is determined by the resistance of the silver trace, which is affected by the resistivity of the ink, and the width of the silver ink [9]. Resistivity is a measurement of how much electric charge a material can oppose [9]. Taking the basic laws of electricity into consideration is an important factor when designing a printed circuit.

With electroluminescent displays, circuit design needs to be taken into consideration, especially with a segmented display. In order to optimize results, silver trace lines should have enough room in between them so that an electrical charge won't interfere with other parts of the segmented display. Silver traces should insure solid connection with the leads and make sure the correct display is illuminated when desired. Other design considerations include the size and the proximity of the common (front electrode) to the phosphor, which can help avoid short circuits. Also, to control illuminating sequences circuits should be open at certain times when the phosphor should be off, and closed at other times. This is achieved with a series of relays, which are devices that are either open or closed at default, and switch to either closed or open when a signal or current is passed into the relay.

As printed electronics continues to improve and grow as an innovative technology, the proper research and development is necessary. The combination of functional materials and traditional printing practices opens the door for a variety of creative applications. This project intended to discover an optimal way to design the functional material into circuits for graphic displays.

Chapter Three - Methodology

The purpose of this study was to answer the research question of if different variables of designing electroluminescent circuits have an impact on circuit performance. Performance can be defined as the ability to illuminate and the amount of resistance created. Experimentation was used to find the cause and effect relationship between the design and circuit performance and was quantitatively analyzed to determine optimal circuit performance.

Part 1- Preliminary Testing

In order to test the different variables of designing an EL display, a preliminary test was conducted at the Graphic Communication Department at Cal Poly. The test consisted of varying silver ink area sizes, the distance from the power supply, the width of power lines, and isolating a common (See Appendix A for Preliminary Test Layers). The following procedure was used to conduct the preliminary testing:

1. Using Adobe Illustrator, construct a 7in x 10in test file. First, create a 50mm x 50mm square with a power line that is 1mm x 10mm and 5mm x5mm connector square. This is the standard test square for the average of all the different tests. Next, for the silver area test create two more test squares that are 10mm x 10mm and 100mm x100mm, both with standard power lines. For the distance from the power source test, create two standard squares with power lines of 1mm x 50mm and 1mm x 200mm. For the width of the power line test, create two standard squares with power lines that are 0.5mm x 10mm and 2mm x 10mm. All of the test squares mentioned above share the same dielectric, phosphor, and are placed under one common. Finally, construct a standard test square with its own individual common. Output each layer (silver, dielectric, and phosphor) as individual PDFs.

2. Next, prepare three 305tpi mesh count screens by degreasing and washing them; one each for the dielectric, silver, and phosphor. Once clean, coat the screen with a capillary film emulsion by RyoCap. The test files are then output onto a transparency film and exposed onto the screens using a NuArc 3140 exposure unit with a 60 second vacuum and 60LTU. After exposure, the screens are washed and dried using a power washer.
3. First, load the phosphor screen into the Automatic Screen Printer and apply the ink to the top of the screen. Make sure the machine settings are correct. Print onto the ITO transparent film then run the film through the oven at 925 degrees for 60 seconds.
4. Replace the phosphor screen with the dielectric screen and print two layers of the dielectric ink. Run the film through the oven.
5. Make sure all layers are in register. Repeat step 3 with the silver screen.
6. Once the printing is completed test the functionality and conductivity of the different segments and record.

This test was conducted to get a better understanding of the different variables, such as silver trace length and width and the image size, for creating printed circuits.

Part 2 – Implementing Results in a Segmented Display

The results gathered from the preliminary test were used to build a segmented electroluminescent display for a graphic design. The purpose of this step was to see what circuit design is practical in a design that would be produced for consumers, while using the preliminary test results to construct an optimal circuit design.

After analyzing the procedure and resistances from the preliminary testing, a segmented circuit was designed to implement the preliminary findings. A test design file was created

in Adobe Illustrator with nine individual displays combined into one graphic design. After the preliminary test, production techniques were changed slightly to optimize results for the segmented display. The design was printed using 156 tpi screens and drying times between layers was increased. See Appendix B for Layers of the Graphic Display. Requirements for the segmented display included being printed on a transparent ITO sheet and a concentric circle design.

Part 3 – Powering the Display

In order to control the sequence the individual displays were illuminated in the printed ITO film was attached to relays on a breadboard, an Arduino Board, and a 5A power source. The control test started with a function generator that supplied 2V to the breadboard controlled by the relays. The Arduino Board, supplied by 12V through a USB connection to a computer, was wired to the relays. All the relays ground were linked together and sent back to the Arduino Board. The relays would let the 2V pass only when the Arduino Board sent the output to high and would not conduct when output was sent to low. When the relays did conduct, the current passed through the LEDs, illuminating them. Finally, the display was placed in a picture frame with the wires securely fashioned and code was written to control the lighting sequence. The design was evaluated on performance and measurements were collected using a multimeter.

Chapter Four - Results and Discussion

Part 1- Preliminary Testing

The test design was created to test different variables of a printed circuit. Three different aspects were tested: area, length, and width. The differences in area tested were to see the size possible to be illuminated. The length test was to see how the lengths of the silver traces could be effective. Finally, the width test was to test if the width of the trace line affects the performance of the circuit. Figure 3 includes labels of all test segments and blue areas represent the areas of the test that were functional.

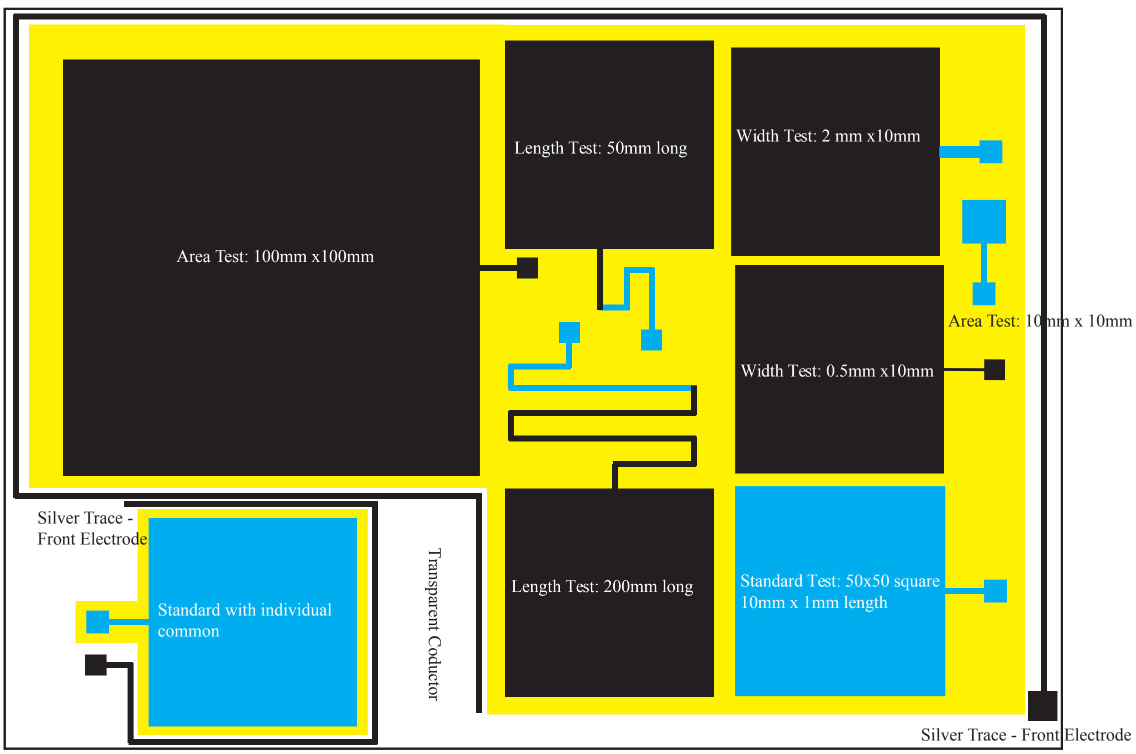

Figure 3 — Preliminary Test Results

Although the preliminary test did not produce the desired test results, valuable conclusions were still made that helped in the development of the graphics test. The length test was to test if the distance from the power source affects the performance of a display. The

purpose of the width test was to find if the width of the silver trace line from the lead to the image has an affect on performance. Finally, the purpose of the area test was to determine how the size of an image affects the ability to be illuminated.

When measured the resistance decreased the farther the leads were placed from the common lead. Another observations was that in the length test the phosphor in the silver traces would gradually illuminate more of the phosphor on the silver ink line the longer the leads of the power source were held on the test. Analysis of the test also brought to attention the issue of traces illuminating two segments when sharing a common dielectric. The observations were very useful in design and production considerations for the segmented design. Beneficial factors to consider included drying time between printing layers, changing the screen mesh, and the issue of a common dielectric. The findings from the preliminary test were used to configure the circuit design for the segmented display.

Part 2 – Implementing Results in a Segmented Display

One of the main areas of focus was the development of a graphic design that included multiple circuits. After much consideration, the original design was changed from containing 15 individual displays to only nine. This change was made to accommodate some production limitations and to simplify the printing process. One such limitation was the use of

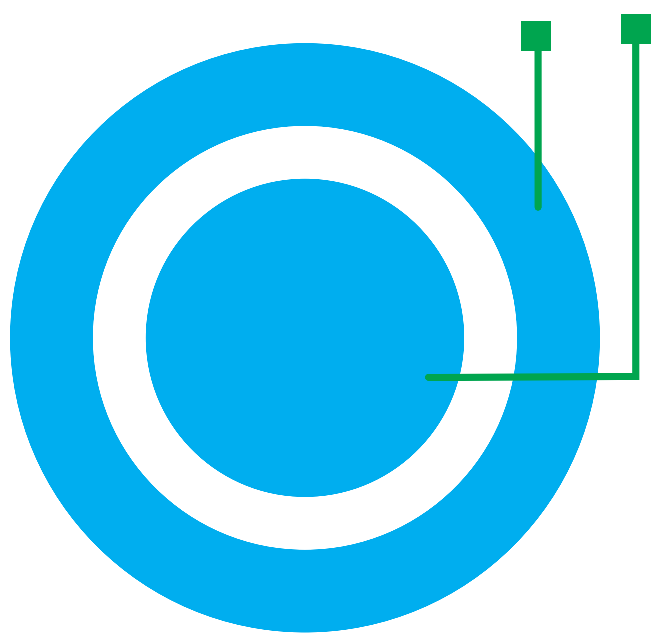

Figure 4 — Issue with Concentric Circle Design

an ITO sheet that acts as a front electrode in the stacking process. The ITO creates an electrical field wherever phosphor is layered. Due to the original design being concentric circles this left the issue of silver trace lines passing through phosphor to supply power to inner circles. If a silver line crosses through an outer circle it would then light up both the inner and outer circles. A possible solution would be to create multiple layers of dielectric to create a "bridge" that would prevent the silver trace from supplying power to unwanted sections of the display.

However, in order to ensure a functional display, the idea of removing a few displays to create room for silver trace lines to pass through was created.

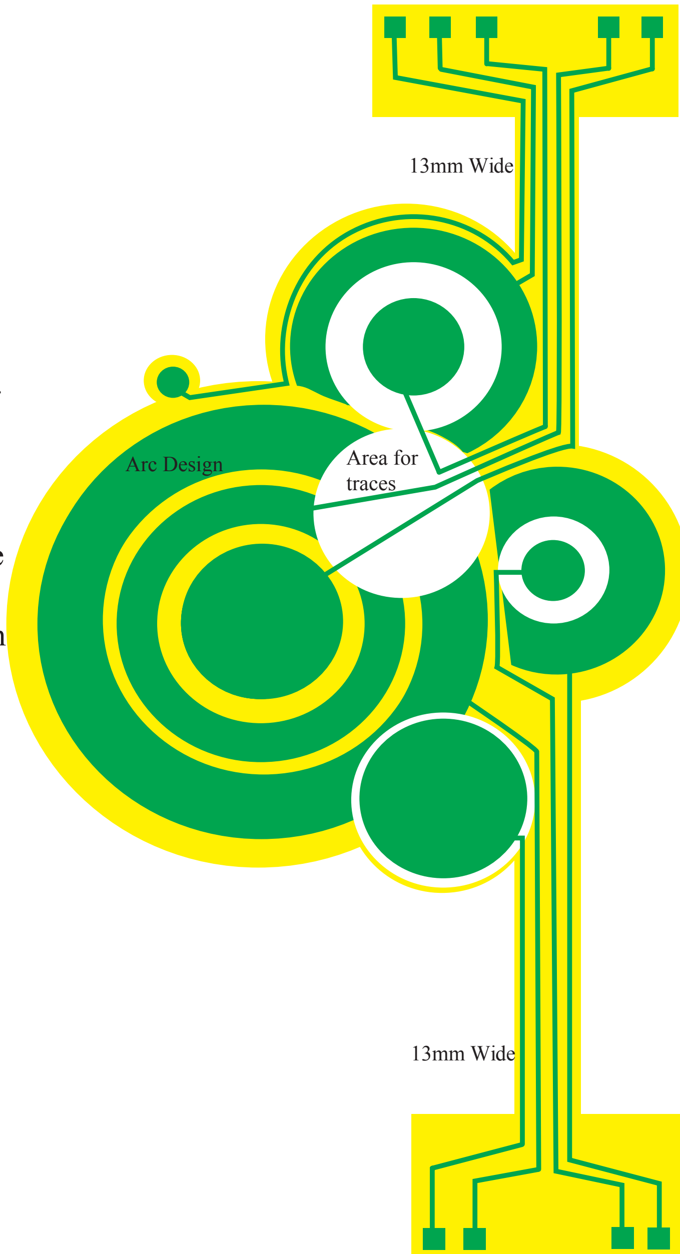

Figure 5 — Circuit Design Considerations; Green represents silver ink and yellow represents Dielectric ink

This allowed for a simpler printing process with the resources available. Another solution to avoid using concentric circles was to create arcs that would appear as circles when hidden behind another display or part of the non-electrical graphic. Figure 5 shows an example of how arc shaped rings can appear as concentric circles when intersected by another circle. Changing

a centrally located circle originally intended to be a printed circuit into a traditionally printed graphic created room for the silver traces lines to pass through the graphic to supply power to circles farther away from the leads. This allowed for both a way to hide the trace lines as well as avoid coming into contact with unwanted phosphor segments.

Integrating traditionally printed graphics with printed electronics played a key role in creating a segmented display without detracting from the graphic design. One requirement for the graphic design was to hide the silver traces and dielectric ink that would detract from the display. A separate graphics layer placed on top of the printed circuits was used to hide unwanted visible layers of the circuits, such as the dielectric and silver traces, because of the transparent substrate requirement. On a strip of dielectric, silver trace lines travel up and down the film sheet to connect the leads to segments of the display to supply power to illuminate the phosphor. In order to hide the dielectric and trace lines, a strip of black ink was incorporated into the design. As seen in Figure 5, the width of the dielectric strip (13mm) had to be wide enough to accommodate all of the traces lines, as well as the dielectric. To keep the strip at minimum width, five traces stem from the top of the display and four stem from the bottom. Each line is 1mm wide and the top traces have 2mm in between lines while the bottom four traces have 3mm between lines. The same design tactic was used to hide the dielectric and front electrode layers of the circuits. A black stroke was incorporated around the circles to hide the trace lines travel to the individual segments.

Part 3 – Powering the Display

Another area of focus was developing a way to connect the wires from the power source to the ITO film. The major problem found was that the wires had trouble staying attached to

Figure 6 — Numbered Segment Display

create the necessary connection needed for the display to light up. Originally, tape was used to adhere the 10 wires to the ITO (nine for each individual light and one for the common), but any movement of the film would cause the wires to become dislodged or wouldn't provide a solid connection. The next option considered was to solder the wires to the ITO film. After a quick test, this option was quickly dismissed because the melting temperature of the ITO is less than the temperature required for the solder. Finally, the decided upon solution to secure the wires to the ITO film was to adhere the wires with tape and then apply pressure to hold the wires down. Pressure was applied by using a wooden stick taped down on top of the wires. Also, the display was placed in a picture frame with the back of the frame adding pressure on the wires. This proved to hold the wires in place and created a secure connection if done properly. The results proved to be sufficient, with the exception that Segment 3 didn't light up. A possible cause could be that the wire was not securely attached before the pressure was secured to the ITO. Overall, the application of pressure to the wires proved to be a functional solution.

An additional decision on the construction of the graphic display was deciding how to power the display to illuminate all nine segments with equal brightness. Construction of the controls took place with nine relays connected in parallel between the power and the EL display.

This was done through the use of a breadboard, the white rectrangle with holes in it in Figure 7. Connections were made with wires soldered to the relays. These were linked to a common ground for the AC current, shown in black, and a common power source for 120V, shown in red. Also, in red is each of the wires connecting individual relays to the 5V digital outputs in the Arduino Board. Wiring the displays in parallel proved to provide sufficient power to illuminate all nine displays using a 5A Backlight power source.

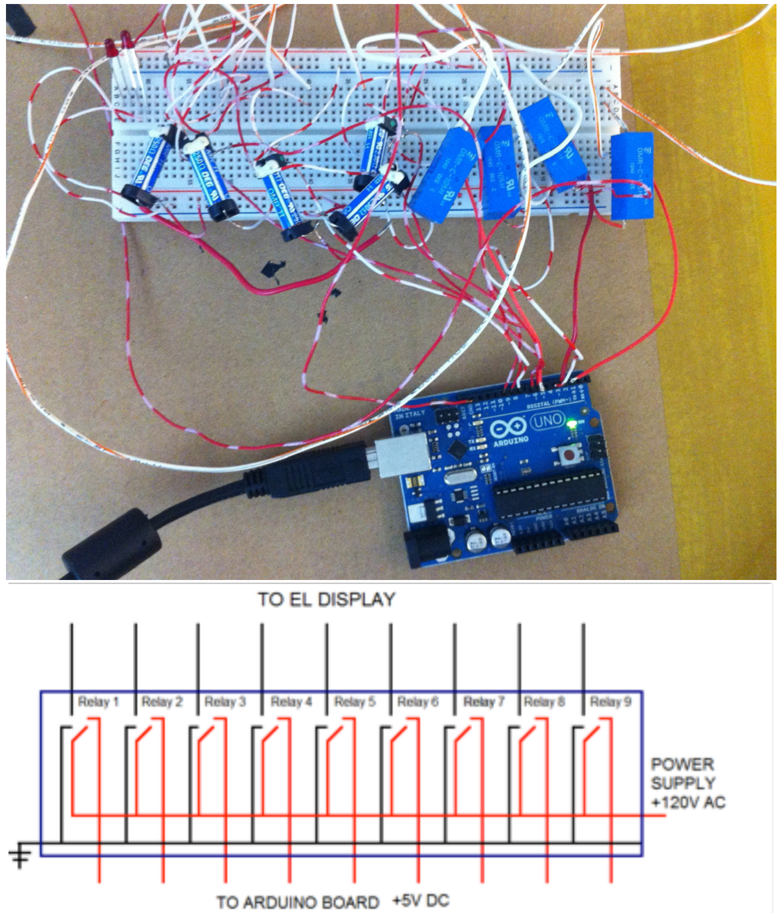

Figure 7— Relay Design

To illuminate the sections in the right order required control of when current was allowed onto different areas of silver ink. A passive matrix involves the controls of the circuit where the relays interact with the power prior to entering the display and only allows certain segments to light. The Arduino Board is provided a current from a 12V battery, which then sends out 5V signals to the relays. Once the particular relay receives 5V, it goes from open (off) to closed (on), allowing the current to pass through that line. Then, when the Board no longer sends the 5V, the relay opens and that sequence stops illuminating. Using a passive matrix allowed for manipulation of the lighting sequence to produce a unique display when desired. A control test

was done with a function generator that supplied 2V to the breadboard controlled by the relays. The relays would let the 2V pass only when the Arduino Board sent the output to high. However, they would not conduct when output was sent to low, as shown in the code below. When the relays did conduct, the current passes through the LEDs, illuminating them. Through the three relays, a small light sequence occurred, illuminating one of the LEDS in a one second interval and leaving them on for two seconds.

```
//First test relay code for three relays
//assign relay numbers:
const int relayOne = 0;
const int relayTwo = 1;
const int relayThree = 2;

void setup() {
  //initialize the relay as an output:
  pinMode(relayOne, OUTPUT);
  pinMode(relayTwo, OUTPUT);
  pinMode(relayThree, OUTPUT);
}

void loop(){
  digitalWrite(relayOne, HIGH);
  digitalWrite(relayThree, LOW);
  delay (1000);
  digitalWrite(relayOne, LOW);
  digitalWrite(relayTwo, HIGH);
  delay (1000);
  digitalWrite(relayTwo, LOW);
  digitalWrite(relayThree, HIGH);
  delay (1000);

}
```

Figure 8 - Complete Display with Graphic

The EL display was able to successfully light up 8 of the 9 segments in the design. The one failed segment was probably due to a lack of a secure connection between the wire and the trace. However, after about a minute, heat from arcing occurred at the front electrode in the ITO

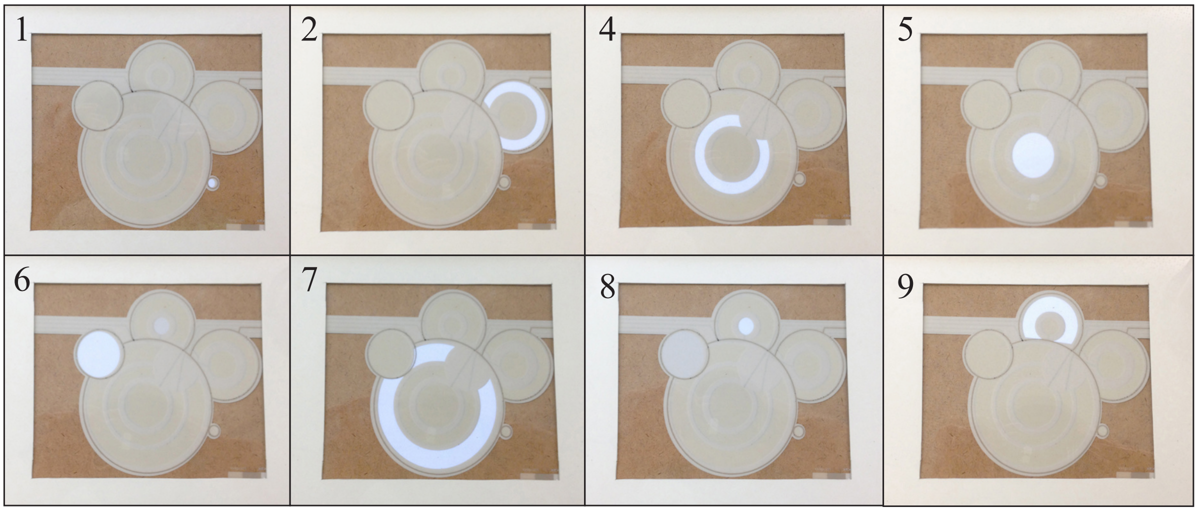

Figure 9 - The eight functioning segments illuminated.

began to burn, causing smoke on the glass of the picture frame. The arcing could have occurred between the ITO film and glass of the picture frame. This arcing could have been caused due to pinholes in the dielectric, which could have occurred during the printing process. Further research can be done to analyze the source of arcing and how to prevent it.

After producing a functional segmented EL display, multiple recommendations can be made for future circuit designs. In regards to the production process, circuit design should be carefully crafted for desired products. Trace lines should be able to be incorporated into the graphics without being too noticeable if the background needs to be transparent by using a graphics layer to hide unwanted circuit parts. Another recommendation for trace lines is to avoid crossing over phosphor areas to avoid illuminating unwanted segments. Also, the distance the trace has to travel should be kept short to provide less resistance. The 156tpi screens seemed to produce better quality circuits than the 305 tpi screens. A possible reason is because a 156 tpi screens tend to produce less resistance in the silver trace lines than the 305tpi screens. Lastly, a very important design consideration is to figure out how to securely fasten the wires to the ITO film while still making the display look presentable. However, further research can be conducted on how to design and wire the power supply.

Chapter Five - Conclusion

The intent of this study was to explore the design and production tactics for a segmented electroluminescent display and provide recommendations for the growing field of printed electronics. The area of a display and the proximity of the common are all important variables to take into consideration when designing a segmented display. Due to the multiple ways to build a printed circuit there are some recommendations that could help in the future development of printed electronics. The preliminary test revealed problems with a universal dielectric housing multiple segments. Also, the preliminary test contributed to the design considerations of the graphic display in relation to silver trace lines. Results from the segmented display design provided a functional display that concluded in multiple recommendations for future experiments.

The findings and recommendations from this study can be used as a foundation for further studies. Proposed future test can be done to find a more efficient and secure way of attaching the wires to the ITO film. Also, ways to prevent arcing can be developed to solve the problem of potential burning of the ITO. Electroluminescent displays still have lots of room for development and improvement, but by examining this study recommendations can be made for the design of a segmented display.

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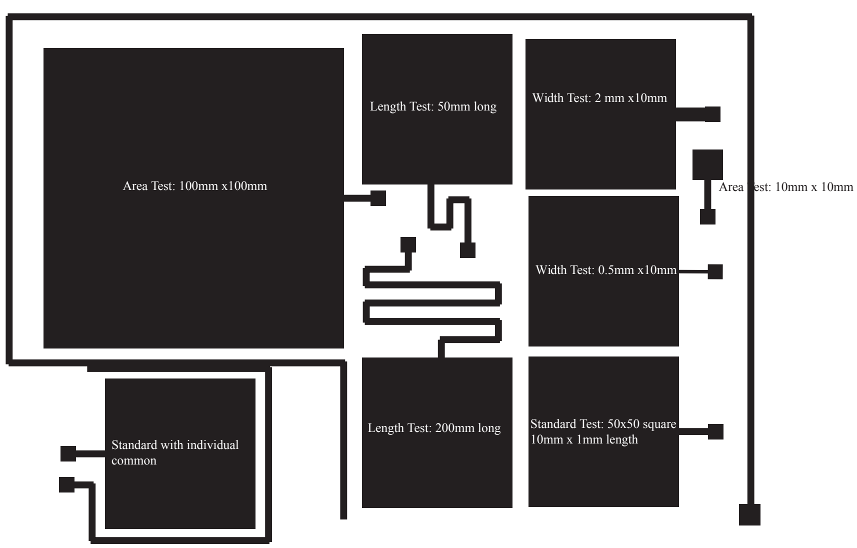
Appendix A - Preliminary Test Layers

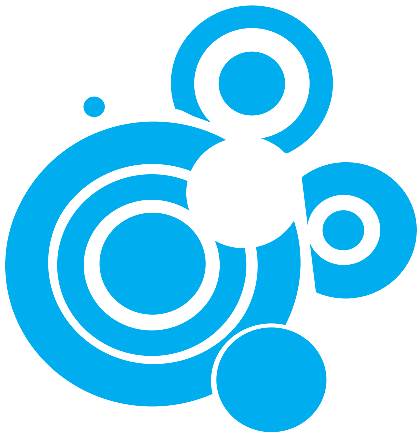
Phosophor Layer

Dielectric Layer

Silver Layer with labels

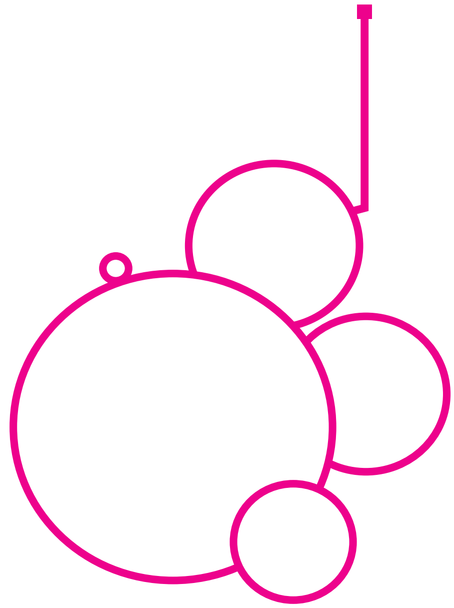


Appendix B - Ink Layers for Graphic Test

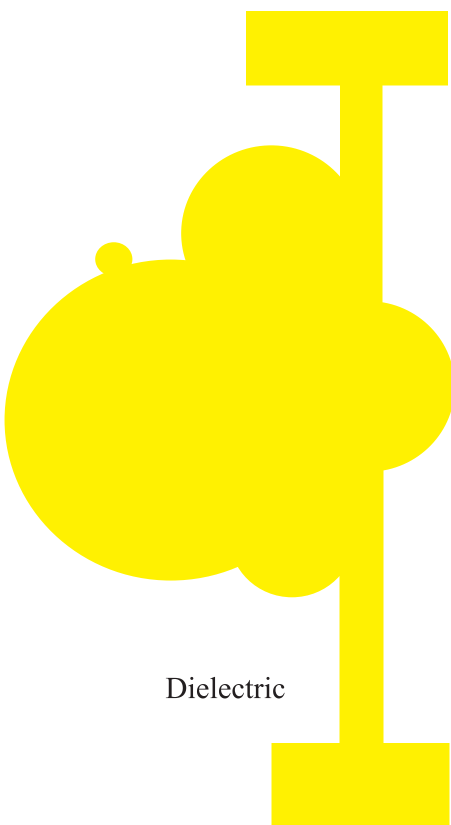


Phosphor

Silver Ink - Back Electrode



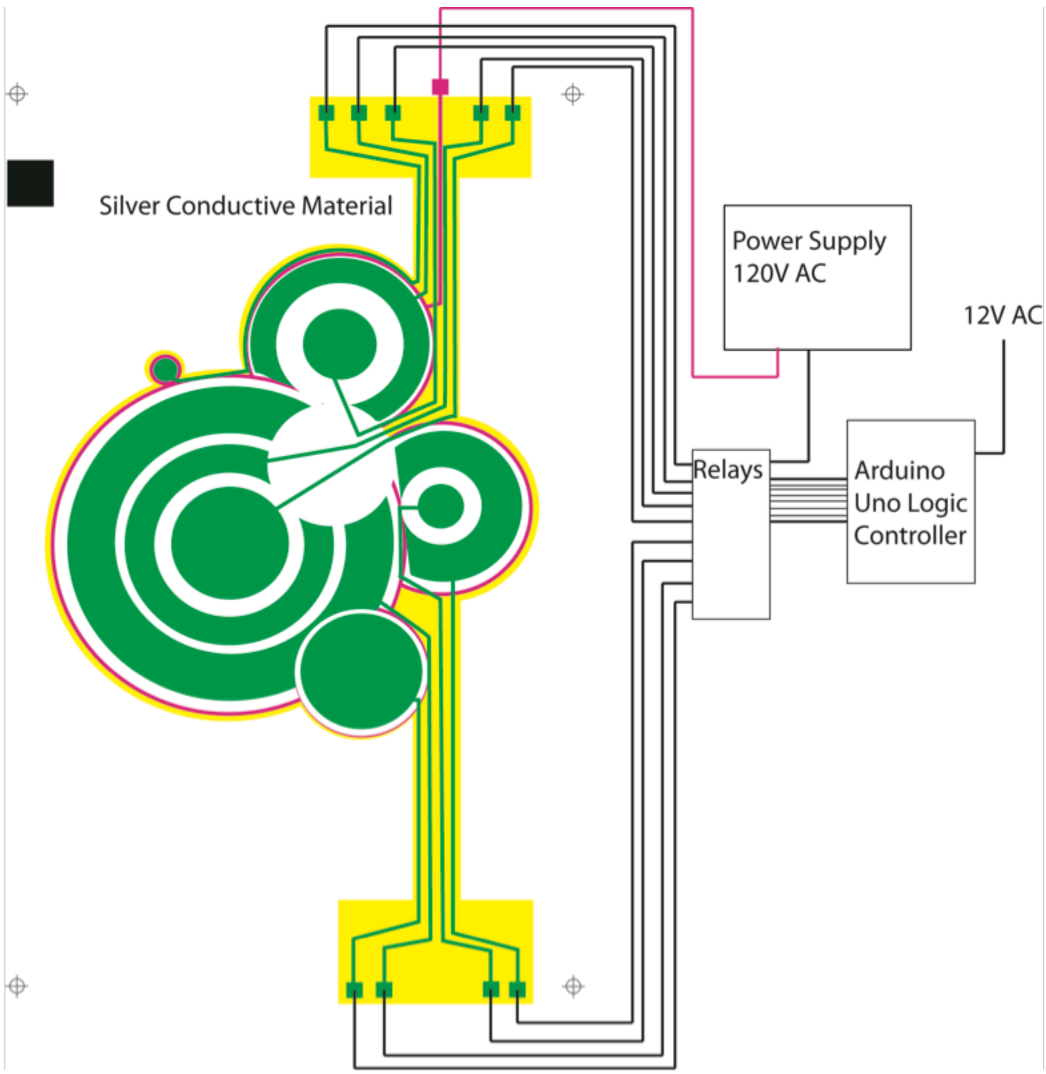
Silver Ink - Front Electrode

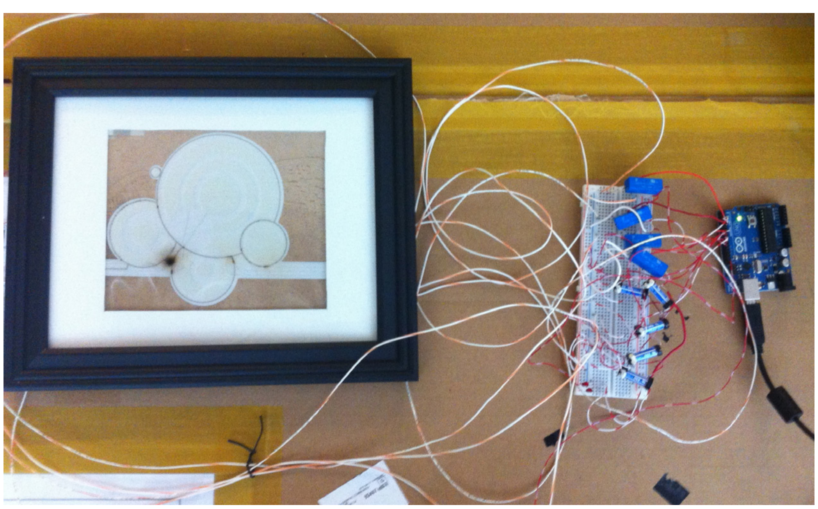


Dielectric

Graphic

Appendix C - Display Layout





Appendix D - Graphics Layer Cover Up

The Graphics Layer is used to cover the Silver (Back Electrode) and Dielectric Layers that would detract from the design appeal of the display. The Graphics Layer was printed separately and then placed on top of the display. Note the black borders to hide the other layers due to the transparent substrate requirement.

Graphics Layer

Silver and Dielectric Layers