Printed Electroluminescent Display

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2012

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Abstract

Electroluminescent displays are part of an emerging technology known as printed electronics. Most identify printed electronics with purely electronic purposes such as the Radio frequency identification (RFID). Now the electronics and graphic communication industries have come together to create of new forms of products that interact with customers. Flexible, electronic circuits use 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. This paper focuses on creating an interactive electroluminescent (EL) display. In selling a product, displays are important because most customers purchase a product for the first time based on how the product draws customers' attention. The display's purpose is to create point of purchase advertising that draws the customers' attention to the product advertised by the electroluminescent display over other conventional displays in a store.

The electroluminescent display features a design that involves nine segmented shapes which illuminate at various time intervals. The Arduino board controls the pattern for illumination by using a control system made of nine relays. Blue phosphor illuminates, or backlights, the surface which has a colored design on the front layer to brighten the design. Typical screen printing process creates the colored design on the surface. The display is 70 µm thick, 8 inches wide, and 5.5 inches high. The area outside of the display is transparent at 8 x 10 inches. A 60 Hz, 120VAC source powers the EL display.

Chapter 1 - Introduction

An electroluminescent display is a display created by covering the both sides of an electroluminescent material such as phosphor with conductors. An electroluminescent material is a material that lights up when a current passes through it. The display is generally made through screen printing or spin coating [7], to create a circuit with various layers of insulation and conductive material micrometers in width. Circuits produced this way are known as printed electronics. An electroluminescent display differs from devices such as monitors because the display turns off when the electrical charges stored on the pixels disappear. and when turned on all the pixels illuminate, removing any previous images shown when it was on [9]. Screen printing also fabricates the EL display, so it illuminates when current runs through the conductive ink, commonly silver. The conductive ink acts much like a wire would, except with more resistance in the ink than a wire would have. Once current travels across the ink, it produces a charge in the phosphor between dielectrics causing the phosphors to emit light [6]. The light emitted can be white, or variations of blue, green, and red light. Because ink has more resistance than wire, the electroluminescent display requires more voltage than a LCD device running between 5-10V.

Electronic displays have typically been used in areas for point of purchase. These are areas where the customer actually purchases the product [11]. For instance the display would be placed at the checkout counter at a fast food restaurant to promote a new product. Electronic displays attract more of the customer's attention than displays printed on paper substrates, a primary reason a customer will buy a new product [11]. Electronic displays attract more attention through by altering light to create the illusion of motion. This motion focuses the brain on the object more than stationary designs. The cost of an EL display prohibits use for individual product packaging, so point of purchase becomes the ideal application.

The most common electronic displays are cathode ray tubes (Scoreboards or old TV screens), liquid crystal displays (LCD), plasma display panels (Plasma screen TVs), and Light Emitting Diodes (LED) [1]. The electroluminescent display presents a unique opportunity because it costs less than a plasma display of the same size, has thin dimensions, unlike the bulky cathode ray tubes, and can be viewed from a variety of angles, a problem for LCDs [1]. Also, EL displays use printed artwork giving them a clearer and more distinct design than displays made with an array of LED lights.

Production and manufacturing techniques for EL displays have still not been optimized. Printed electroluminescent inks are much less power efficient than a printed circuit board. For electroluminescent displays to compete against traditional electronic displays, EL displays must achieve the same attraction of traditional electronic displays with limited extra expenses. Uniform ink surface smoothness, fine lines, and registration are key factors in determining the quality of printed electronics. An electroluminescent display requires an even electron distribution across the substrate so that the display has equal brightness [6].

This project intends to prove EL displays offer a unique design that will find its own niche in the future of advertising.

Chapter 2 - Literature Review

As an emerging technology, the development of printed electronics uses a combination of traditional printing processes and innovative thinking. The concept of printed electronics dates back to the early 1900's with Thomas Edison's idea of using conductive particles and polymer-based adhesive to build circuits [6]. It wasn't until the 1940's 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. Once such process is screen printing; which provides desirable characteristics for printing functional inks. Screen printing is the process of pushing a viscous liquid through a stretched mesh [12]. The thread count and the diameter of the threads of the mesh affect the transfer rate of ink onto the substrate [12]. 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 a proper screen is selected, a photosensitive emulsion (or stencil) coats the screen, blocking the non-printing area of the screen [18]. Then, an image is printed onto a transparency. Ultraviolet light

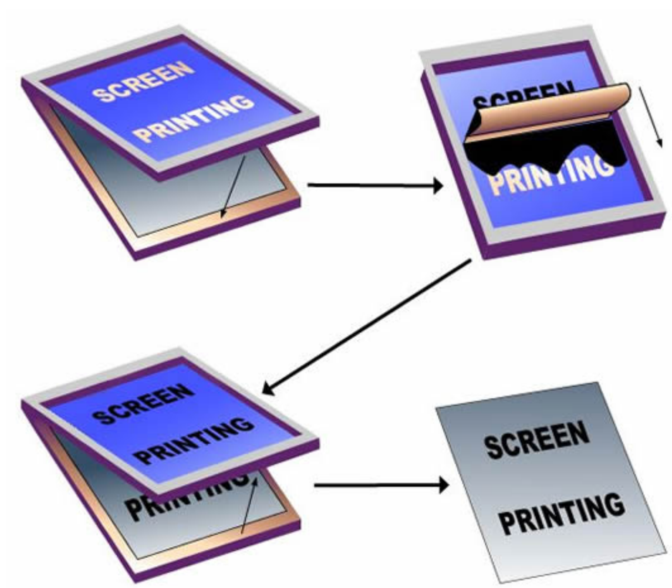

Figure 1 - Screen Printing Process

exposes the transparency onto the emulsion. Then water washes away the unexposed emulsion, leaving an area for ink to transfer through the mesh. The prepared screen is then loaded into the printing press. One edge of the screen has ink placed on it and a squeegee blade pushes the ink through the mesh onto the substrate as shown in figure 1.

Screen printing provides many desirable characteristics necessary for printed electronics. The use of screen printing is highly advantageous in the production of printed electronics due to its versatility and ease of use. The ability of screen printing to create uniform ink films provides one advantage. However, the process must be monitored closely to ensure the functionality of the inks [3]. The ability to print on a variety of substrates, such as the flexible films necessary for printed electronics provides another advantage. The ease of use and print characteristics makes screen printing a valuable resource for printed electronics[17].

The growing field of printed electronics combines traditional printing processes to produce electrical circuits. The use of functional insulators, semi-conductive inks, and conductive inks are used to produce flexible circuits, solar cells, and displays. In 2009, the printed electronics market was valued at $2 billion, with an expected growth of $60 billion in the next ten years, according to IDTechEx [2]. Although there are many applications, electroluminescent displays are particularly desirable for consumer products and displays. Electroluminescent (EL) displays produce a visible light by releasing photons from exciting a substance, like phosphor, and returning it to its ground [4]. EL displays are used for applications such as background displays, control panels, and consumer packaging.

The combination of different materials used to build electroluminescent displays must be arranged in a proper sequence for the printed circuit to function as shown in figure 2. EL displays consist of a layered structure with a front and rear conductive electrodes with phosphor and dielectric layers in between [8]. Particles in the phosphor emit light when an electrical current passes through the circuit. The front conductive electrode typically consists 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 prevents arcing between conductive layers [4]. Specifically in screen printing, the functional inks must maintain certain viscosities and surface tensions to avoid problems. One such problem is "drops that do not bond enough to conduct sufficiently or an excessively rough surface that prevents the next functional layer from adhering" [5]. In order for phosphor to emit light, it requires the application of either alternating current (AC) or direct current (DC). Lower voltages and frequencies are encouraged for longer life spans of the displays [7].

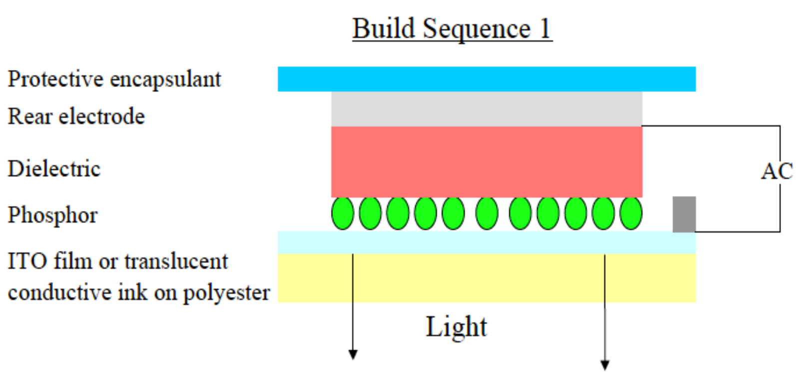

Figure 2 Example Build Sequence of EL display

Understanding of circuits and electromagnetic waves becomes necessary for analyzing the performance of electroluminescent displays. Luminance is the intensity of light, measured in candelas per square meter. When the printed circuit connects to a power source, the silver ink is charged with a negative potential. The rear electrode on the other hand is charged with a positive

potential. Potential can be thought of as a rock on a cliff. It has the potential to fall down to the ground below. In circuits however, the energy involved is electrons wanting to fall to a neutral charge or “ground.” Between the charges is the dielectric. The dielectric is 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. The “displacement” part comes from the fact that the current that actually interacts with the phosphor does not come from the silver ink, but rather from the electromagnetic field generated by the difference in potentials between the front and rear electrodes. This current continuously moves through the phosphor in the circuit [9]. How much displacement current can travel through the silver trace to interact with the phosphor determines the intensity of the luminescent. The resistivity of the ink, and the width of the silver ink affects the resistance of the silver trace, which determines the amount of displacement current. [9]Resistivity is a measurement of how much electric charge a material can oppose [9].

With EL displays, controls are required to determine what the silver trace should light up at different times. A series of relays achieves this. When a signal or current passes into a relay the device, originally at either open or closed as default, switches to its opposite position. Also, to avoid illuminating the wrong area of phosphor when traces cross over multiple areas, dielectric bridges become necessary to prevent the creation of a magnetic field.

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

Chapter 3 – Specifications and Requirements

The engineering specifications and marketing requirements for EL display are listed on the table on the next page. The engineering specifications reflect the constraints and demands required by advisors for the electroluminescent display. These specifications and requirements need to be abstract, bounded, complete, unambiguous and verifiable. Connections between the engineering specifications and the marketing requirements are also required. The design for the display depended on exact specifications. The marketing requirements are important as well because EL display needs to be commercially viable. In a hypothetical situation, the project advisor would represent a client who would want to sell this design commercially.

TABLE I

ELECTROLUMINESCENT (EL) DISPLAY REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements	Engineering Specifications	Justification
1, 2, 3, 4	1. Operates on a 120V Power source without flickering.	For the EL display to work fully it needs a power source between 80-120V. An AC 120V power source from a wall would be ideal.
5	2. Conductive ink lines reach the dielectric material for the display in the most direct path for their area without touching other ink lines or unintended areas of dielectric material.	Unlike conductive wire, conductive ink does not contain pure metal. In other words the silver ink only contains flakes of silver that are mixed in with other materials. This means there will be resistance that can't just be ignored, and longer lines will create more power dissipation, possibly affecting the level of illumination.
1, 2, 3	3. The electroluminescent display lights up each 9 areas of phosphor individually at any time.	To achieve the best result, each segment of the circle must light up outwards towards inwards at varying times, and then dim from outward to inward.
1, 2	4. The poster must be no larger 8" x 10"	The screen printer used to fabricate the EL design can only make designs as large as 8" x 10".
1, 3, 5	5. 5% extra space is made for the EL design for the ideal condition of dot gain. Dot gain is when inks expand when printed on a substrate.	The conductive EL ink must not have the lines touch each other or it will short circuit the display. Dot gain, for screen printing especially, is affected by a wide variety of factors. However in this display spacing is based on assumption of ideal dot gain for screen printing, which is generally 5%[10]
1, 3, 5	6. Display is no thicker than 200 µm	The advantage of an EL display is that it is thinner than a general display lit by LEDs. To prove this, the EL display must be thin.
1, 3, 5	7. The display emits unobtrusive light	Unlike previous designs that only required the ink to illuminate in itself, this EL display already has a design printed on the top layer. Because of that, the color from the EL must not interfere with the color of the design but rather illuminate the design.

Marketing Requirements

1. Low cost
2. Easy to use
3. Can be manufactured in an automated assembly line.
4. Can withstand power fluctuations of +/- 5V
5. Is able to attract customers to the product

The requirements and specifications table format derives from [15], Chapter 3.

Chapter 4–Design

While the design of the EL display art was predetermined for the project, deciding how to illuminate the different sections of the art was left for the project. The two biggest design decisions are how to illuminate the sections in the correct order, and how to provide enough silver ink to conduct the phosphor without running into other areas of silver ink causing a short circuit.

To illuminate the sections in the correct order, the display requires control of when current is allowed onto different areas of silver ink. There are two ways available. The first is a passive matrix, in which the controls of the circuit, involving relays, interact with the power prior to entering the display and only allowing certain sequences to light up. The second way is an active matrix, consisting of transistors inside the display that act like "railroad switches" that direct current to another line of silver ink leading to a different sequence.

After weighing both options, a passive matrix was used. This was because an active matrix would require additional complications to the printing process requiring precision the printing machines would be unable to achieve. Also, there would be difficulty with timing the transistors. Passive matrix, on the other hand, is easier to implement and doesn't put any stress on the printing process.

The original plan included 15 segments as shown in figure 3 on the next page. This required the use of 15 relays, an Arduino Uno board, and a multiplexer. The Arduino Uno board provides a current from a 12V battery, which then sends out 5V signals to the relays. Once the particular relay receives 5V, it goes from normally open to closed, allowing the current to pass through that line. When the board no longer sends the 5V, the relay opens and that particular

sequence stops illuminating. However, the Arduino Uno board only has room to control 14 relays, so the use of a multiplexer becomes necessary for the 15th relay. The multiplexer accomplishes this by using the controls for two relays to control illumination for three sequences.

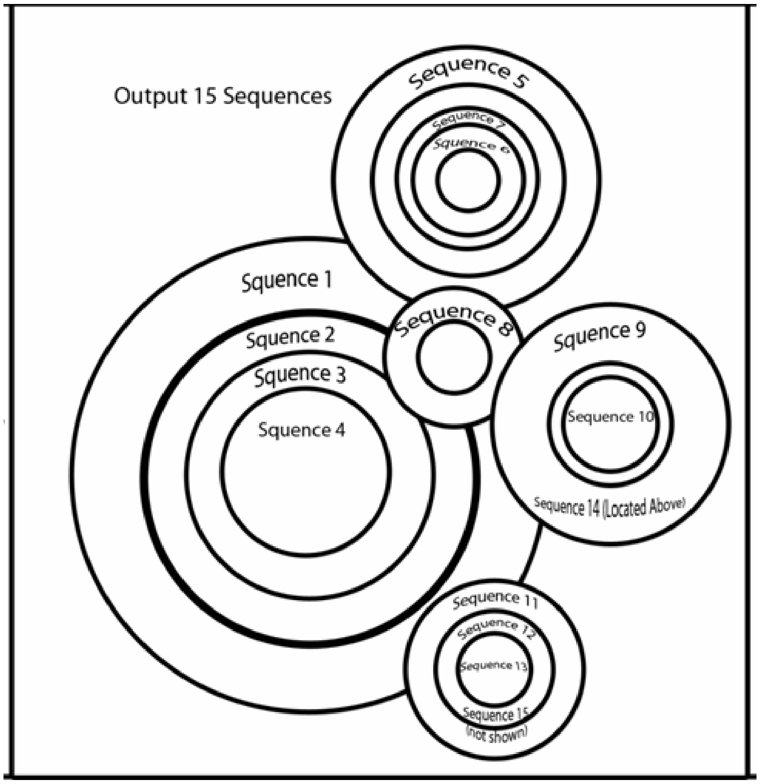

Figure 3 Initial Design

This is done by sending signals faster than the human eye can see to make the appearance that three sequences are on at the same time, when only two are on at once.

This test plan was subsequently changed to a design that required only nine segments to be illuminated at once instead of 15. This was implemented due to constraints on materials and accuracy. This effectively removed the need for a multiplexer, and required only 9 relays instead.

The second design decision was how to provide a path for the silver ink to reach the correct sequences of phosphor without short circuiting. Due to the design being concentric circles this left the issue of silver trace lines passing through phosphor to supply power to inner circles as shown in figure 4. If a silver line crosses through

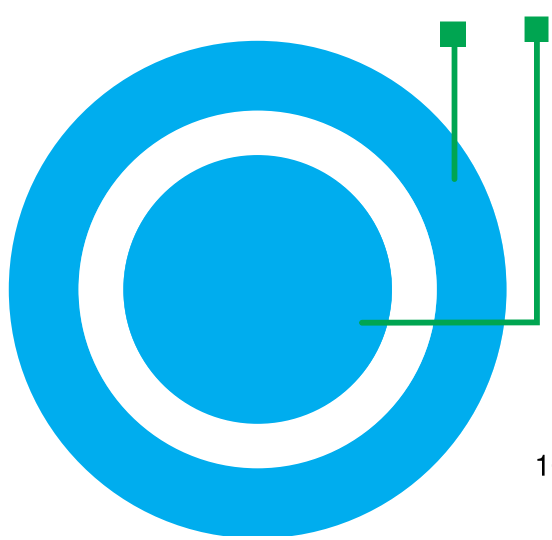

Figure 4 Difficulties with Concentric Shapes

an outer circle it would then light up both the inner and outer circles.

The first idea was to create a second layer of dielectrics and silver ink, where one layer of dielectric would have holes in it that would allow the silver ink to overlap each other without resulting in a short circuit. However, this would ruin the electromagnetic field, preventing any displacement current. The second design idea was to make a diode "bridge" for each of the circles. This would prevent the first layer of silver ink from interacting with the phosphor, allowing the phosphor to light up in the correct areas without resulting in a short circuit. However, this too seemed to have conduction issues due to the use of an Indium Tin Oxide (ITO), sheet that acts as a front electrode in the stacking process. Where phosphor is layer, the ITO creates an electrical field. As mentioned earlier, a possible solution would be to create multiple layers of dielectric to create a "bridge" that would by prevent this. However the dielectric was not thick enough to prevent this electric field forming.

Figure 5 Final Design

This final design shown in figure 5 had nine segments spaced out to create room for silver trace lines to pass through. This allowed for a simpler printing process as well as creating fewer sequences that would have complicated the amount of power needed to light the graphic. Another way to avoid concentric circles shown in figure 4, was to create arcs that would appear as circles when hidden behind another display or part of the non-electrical graphic. The final

design had the illumination sequence set up so that the outer circles would light up first, and turn off last, allowing us to ignore issues of illuminating both outer shapes and inner shapes with the same wire.

Functional Decomposition

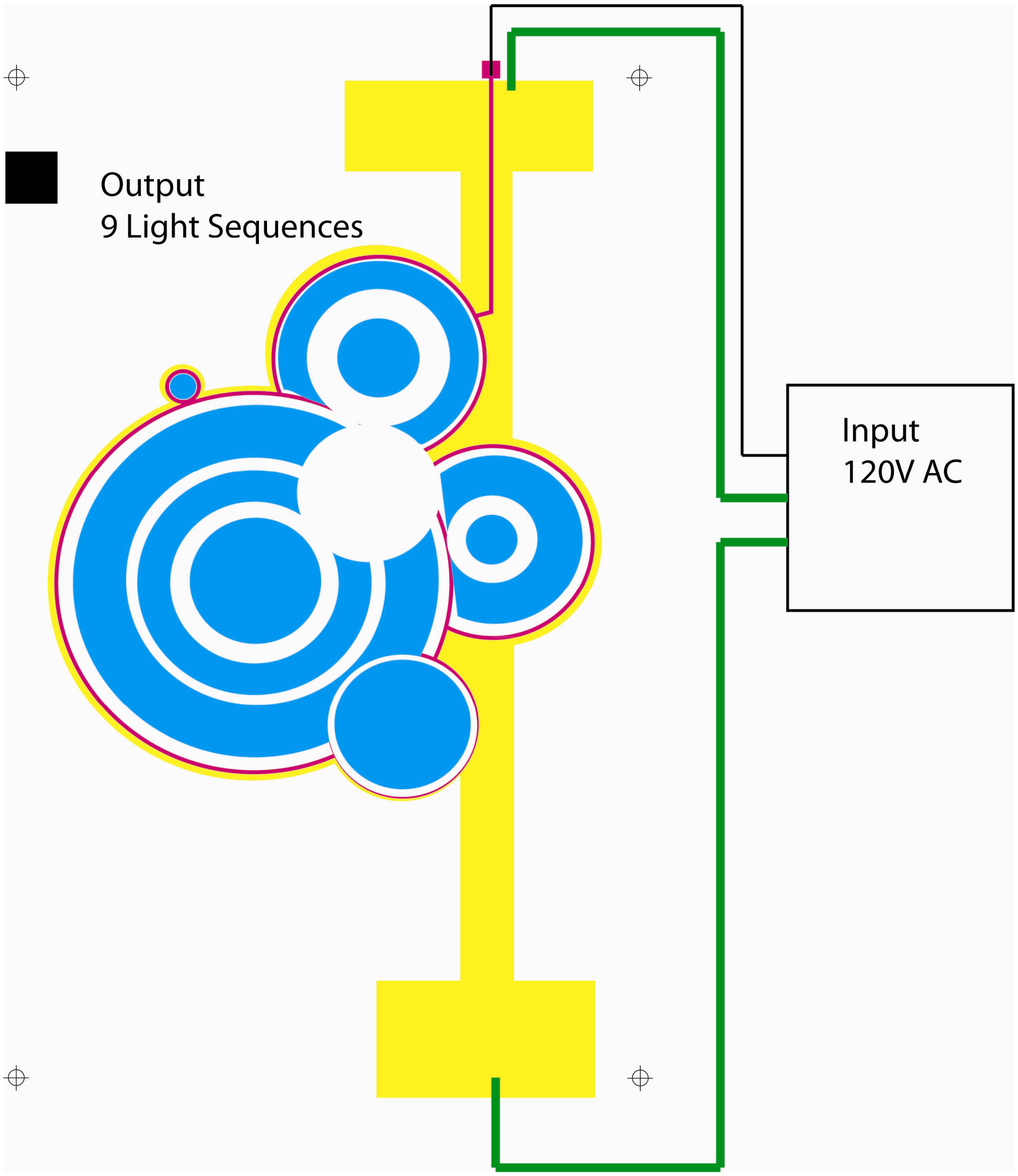

Figure 6: Level 0 Electroluminescent Display functionality

Table 2: Level 0 functional requirements for this design

Module	Electroluminescent Display
Inputs	- Power, 120V AC rms, 60 Hz, will be turned on with a switch.
Outputs	- Light sequences for circles involve sending signals to tell when to begin one output sequence and when to begin the other. Each output pertains to a unique ring in the design.
Functionality	-After being connected to the power source, the electroluminescent display splits power between the 15 zones in the display. Power dissipation has to not exceed 120V for power.

The Level 0 functional requirements table derives from [15], Chapter 5.

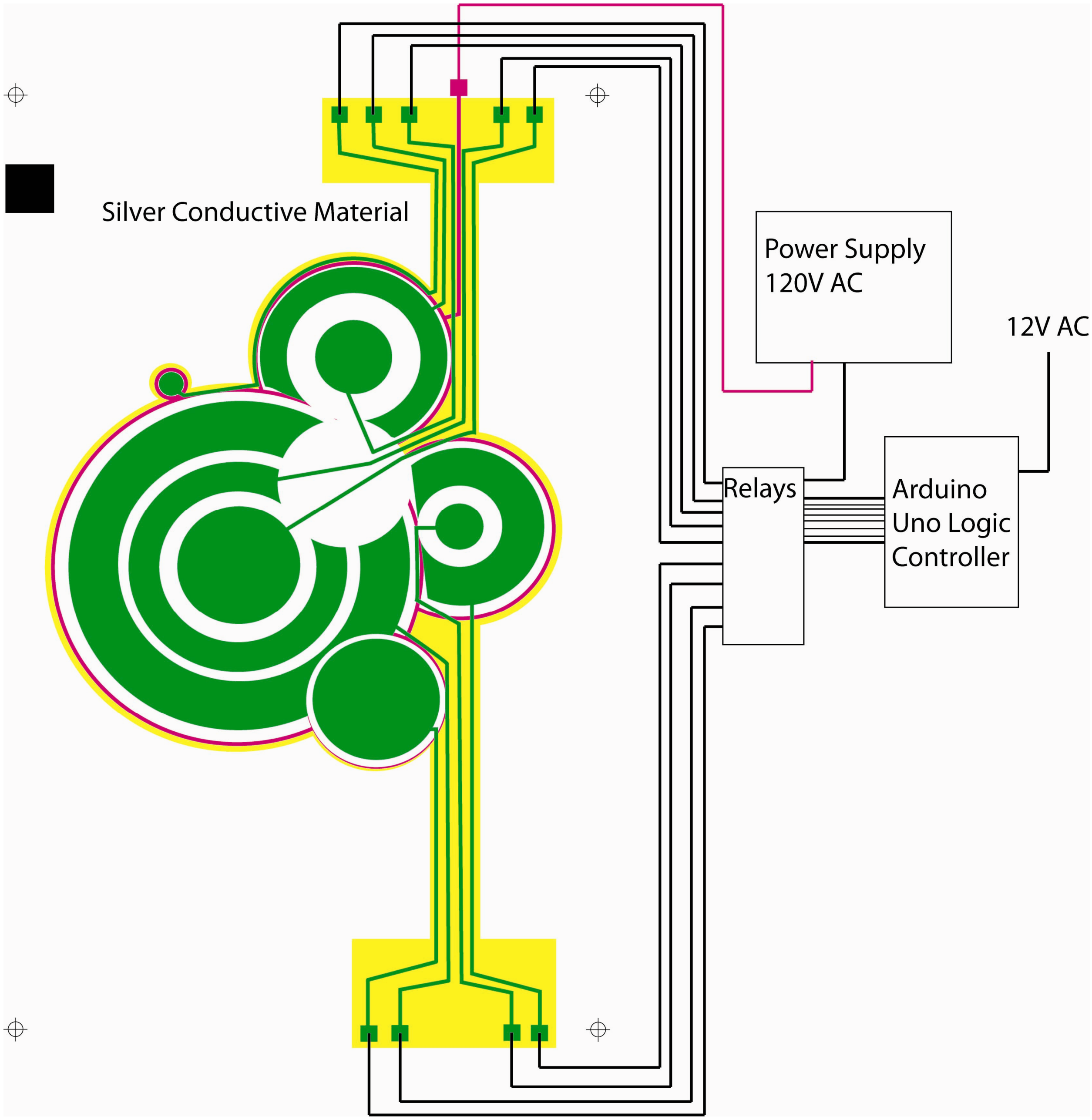

Figure 7: Level 1 Electroluminescent Display functionality

Table 3: Level 1 functional requirements for this design

Module	Relays
Inputs	- 120V AC, 5V AC computer logic signals
Outputs	-Current to n of 15 circuits
Functionality	-The relays take the voltage from the plug and direct it to a specific circuit when a voltage is applied to a particular relay.

Module	Arduino Board
Inputs	- 12V AC
Outputs	-5V AC computer logic signals
Functionality	- The controller acts like a switch which depending on the clock time will connect the voltage to one of the eight circuits.

Module	Silver Conductive Material
Inputs	- Current to n of 9 circuits.
Outputs	-Lights up phosphor in area covered by material
Functionality	- The current goes through the conductive material on the top of the display creating an electromagnetic field which then excites the phosphors to light up.

The Level 1 functional requirements table derives from [15], Chapter 5.

Chapter 5 – Test Plans

Two test designs were made over the quarter. The first one tested the ability of the relays and Arduino Board to create light sequences. The second tested the width, area, and length effects on resistance when covering the phosphor with silver ink for the EL display.

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 the USB in my computer was wired to the relays. The board has the digital output being the "high" part of the code, which sends 5V to relays. All the relays' ground linked together and connected back to the Arduino Board. 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 passed through the LEDs, illuminating them. Through the three relays, a small light sequence occurs, illuminating one of the LEDs for a one second interval then leaving it off 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);
}
```

The EL display conductive material test was more complex and required two parts, the preliminary testing and actual implemented test in the screen printing lab. The test had to meet the specifications listed under table 4.

Table 4: Test specifications

Engineering Specifications	Justification
1. Is 120V able to light up phosphor from 500um down to 200 um trace width? The trace length is 20 cm long and covers 100 mm area of phosphor.	The black line on the EL display covering the wires should be as thin as possible, and the spacing set aside for the traces should be twice as wide as the line itself, so to avoid short circuit with dot gain. Dr. Rong estimates that there is at least a 30% dot gain, but it won't have 100% dot gain required to short circuit.
2. Is 120V able to light up phosphor at lengths from 10 cm to 75 cm? The trace width is 500um wide and covers 100 mm area of phosphor.	This test measures resistance and how much does distance from the voltage source to the load restrict the design.
3. Is 120V able to light up phosphor at areas between $20mm^2$ to $500mm^2$? The trace length is 20 cm long and covers 100 mm area of phosphor.	Since the phosphor trace has to completely cover the area of phosphor that it needs to light up, a third test is required to see how much resistance occurs on larger areas.

The following procedure was used to conduct the preliminary testing with the design on page 19:

1. Using Adobe Illustrator, construct a 7in x 10in test file. First, create a 50mm x 50mm square with a power line with dimensions of 1mm x 10mm and a 5mm x5mm connector

square. This will be the standard test square for the average of all the different tests. Next, for the silver area test, create two more test squares 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 and phosphor, and are placed under one common ground. Finally, construct a standard test square with its own individual common ground. Output each layer (silver, dielectric, and phosphor) as individual PDFs using Rich Black for the color.

2. 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, wash the screens using a power washer and dry.
3. 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 resistance and record the results in table 5 after layers are printed.

The next part is implementing the results in the design. Preliminary testing provided the data to build an electroluminescent display with multiple layers of traces in a graphic design. This step allowed testing on the practicality of the circuit design that would be used for the EL display, while using the preliminary test results to explain the defects in the design.

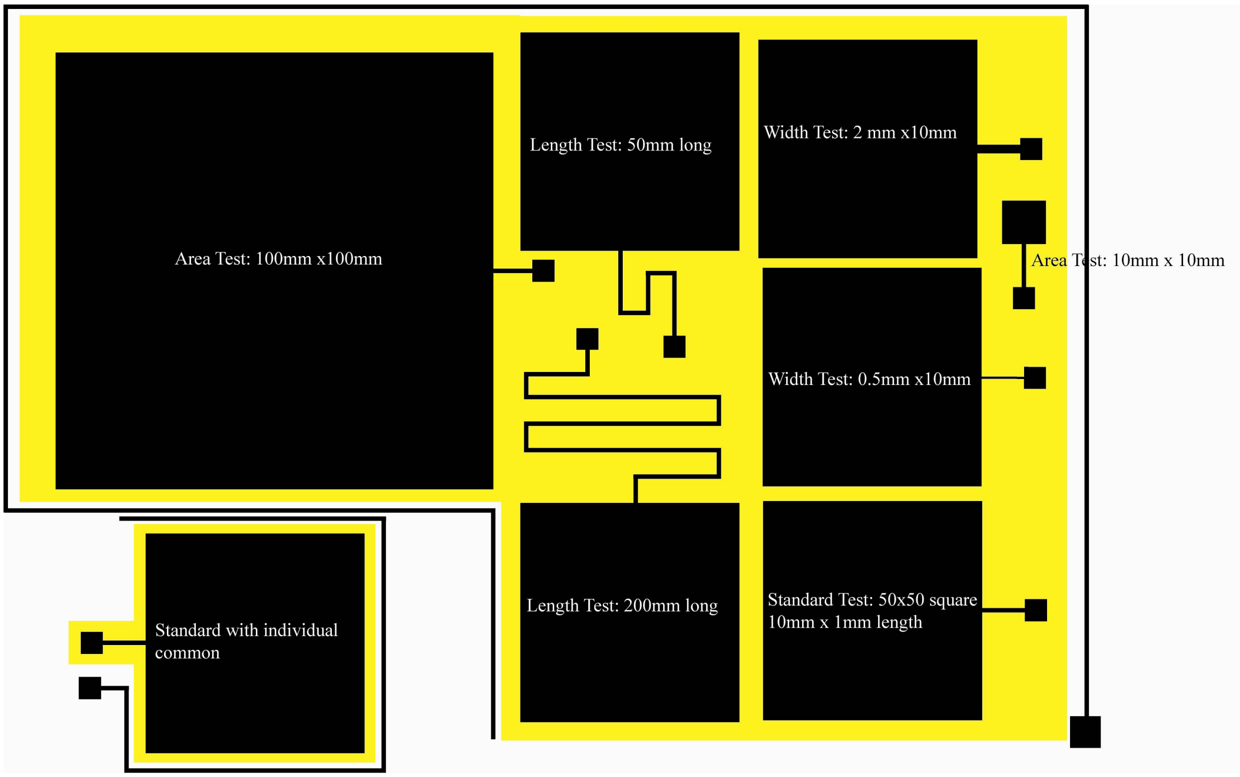

Figure 8 EL test design

After quantitatively analyzing the illumination from preliminary testing, a multilayer circuit was designed to implement the findings. A test design file was created in Adobe Illustrator with nine individual segments combined into one graphic. The lengths of power lines to individual circuits were determined using the resistance results from the preliminary testing. After printing the design using the same procedure as the preliminary testing, the design was evaluated on performance, luminosity, and resistance. A multimeter collected measurements.

Chapter 6 – Development and Construction

One of the main areas of focus was the development of a graphic design that included multiple circuits. Each layer was printed one side on top of each other. The layers were lined up as shown with the registration marks. The inaccuracy of registration was due to the limits of the screen emulsion machine. The final test print design used is shown in figure 9.

Figure 9 Printed design, with Silver traces, Dielectric, Phosphor, and Finally ITO, as shown at top right corner

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 securely attached to the EL 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 ground), 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 plastic on the ITO sheet is 105 C, while the temperature for the 40/60 solder used required 215C. Also due to the solvents in the silver ink, the solder was not able to adhere to the surface of the trace. The next attempt was to use a combination of pressure and tape to secure the wires to the ITO film using tape and then a paper clip to hold the wires down. This proved to hold the wires in place and created a secure connection if done properly. However clips are not an ideal solution, and the tape was damaging to the display. The final design used a picture frame and popsicle sticks to secure the wires with the pressure of being sandwiched between the glass and the back of the frame. This led to the final design shown in Figure 10.

Figure 10 Final Design in process of sequence, 5 segments illuminated

An additional major decision on the construction of the graphic display was deciding how much power was necessary to illuminate all nine segments with equal brightness. In order to figure out the necessary power, it was necessary to calculate how much current each individual display required.

Construction of the relay controls took place with nine relays connected in parallel between the power and the EL display as shown in figure 11. This was done through the use of a breadboard, shown as the blue rectangle. Wires soldered to the relays created the connections that linked to a common ground for the DC current, shown in black and a common power source for 120V shown in red. Each of the wires connecting individual relays to the 5V digital outputs in the Arduino board are also displayed in red. The switches in the relays remain open unless the digital output is high see appendix E.

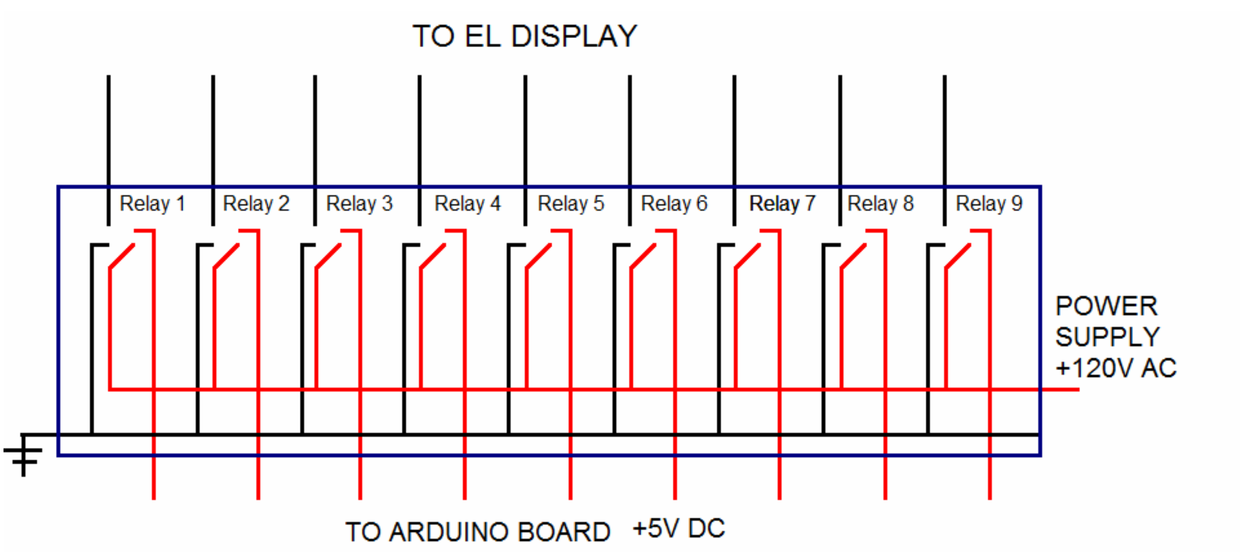

Figure 11 Relay Design

The test code was also adjusted for nine relays, and the final test design. It was also adjusted to test the control sequence, shown in Appendix E.

The first test designs finished fabricating on March 22nd. Out of the six copies made, two did not fabricate properly. With the results, only two of the remaining four designs needed to be tested. The results are shown below in figure 12.

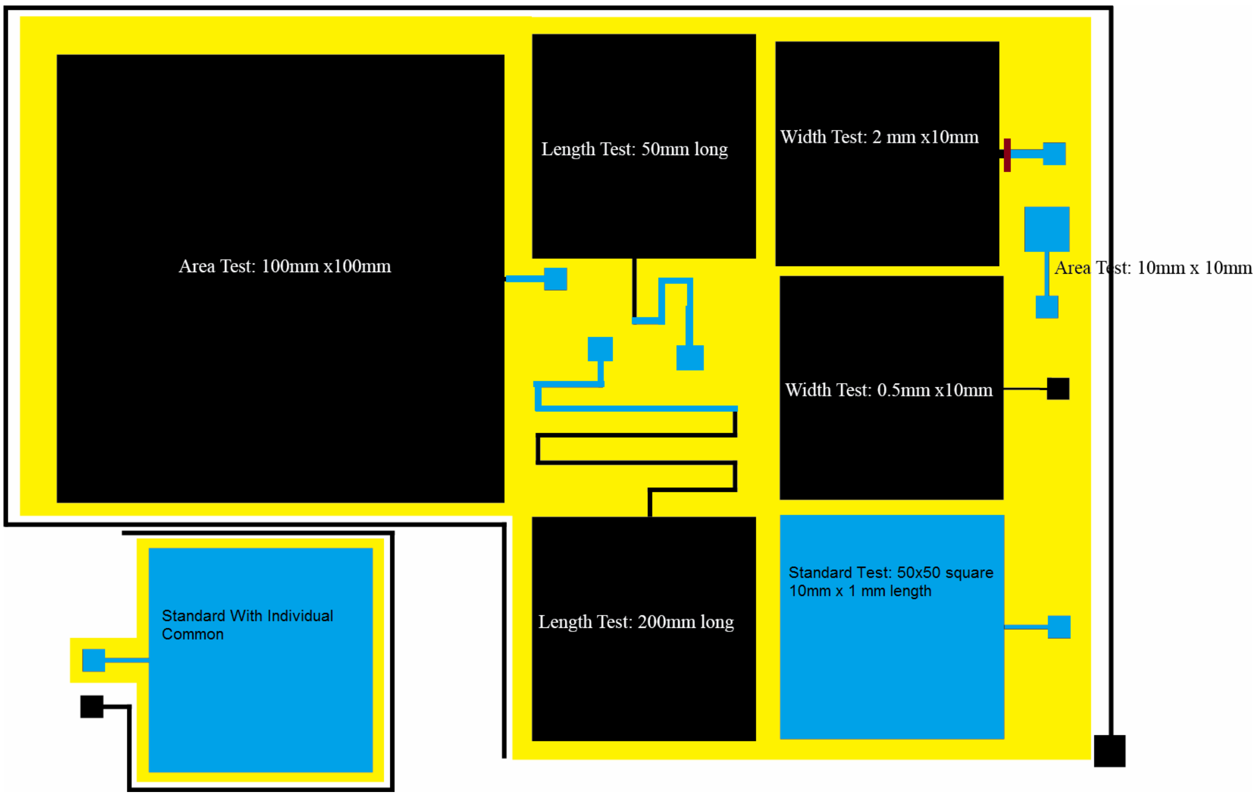

Figure 12 Line width, length, and area test results

The results from both tests were similar enough, that only this report only displays fabrication #1 since it shows the open. The blue colored area represents what portion of the phosphor lit up when 120V were applied to the silver ink. The black area represents the area that did not light up. The red represents where the high current possibly burnt the trace, and created an open circuit. Voltage was applied from the power supply while the EL display was turned so that the illuminating surface was shown. Initial observations showed that the leads would leave

burn marks if pressed too hard directly on the display when connected to the power supply. In the case of the open circuit, it did not leave burn marks. The initial conclusion was the possibility that the high voltage burnt out the silver ink trace. This is like if too high voltage is applied to a diode. It breaks down. The observation of the shorted area having the widest traces and therefore the least resistance, provided the idea that it allowed an abnormally high amount of current to go through the trace and damage it.

Two unanticipated irregularities occurred. First was that the resistance measurements actually decreased the farther away of the placement of the leads. However when the display was tested for resistance a week later, the resistance measurements now behaved as expected. This result most likely was that the display was not completely dry, and certain patches had higher resistivity than the dry areas. The second odd thing was that the squares would slowly light up with the phosphor expanding across the square until the square completely illuminated. This happened on the standard test on the bottom right corner. Also, the phosphor in the traces would gradually illuminate more of the phosphor on the silver ink line the longer the connection of the power source to the test.

The second set of testing began on April 17th. This time the design would become the final design. This test was to see connection issues, how to secure the connection, and how much voltage would it require to illuminate all nine segments. Six copies of the design were produced. On the first copy shown on figure 13 on the next page, five of the nine intended areas of phosphor illuminated when individually connected to the power source. The green parts are the back electrodes, while the pink is the front electrodes (ground). The front electrode is not completely shown due to it being covered by other layers. There is a layer of dielectric between the front and back electrode. The blue parts are where the phosphor did illuminate. The gray

areas are where the phosphor does not illuminate. The second copy of the design, had the connections carefully secured, and all nine segments illuminated when connected to the power supply individually. It was determined that it was connection issues, not registration issues that were the problem. After connecting the design to a power source, three of the nine segments illuminated brightly with a 67V power source. However on the fourth segment, the brightness began to dim. In the second copy conductive tape, masking tape, and finally pressure was attempted to secure the wires to the display. The use of tape to secure the wires ruined the leads of the 2nd copy. In the third and final copy used, an 80V power supply and pure pressure was applied for a secure connection. The following resistance and length measurements are shown below.

Figure 13 Power and Connection Test Results

Table 5 - Trace Lengths and Resistances

Segment	Length (mm)	Resistance
1 (Tiny Circle)	125	168Ω
2 (Top Circle Outer)	61	173kΩ
3 (Top Circle Center)	131	92.3Ω
4 (Big Circle Middle Ring)	141	200Ω
5 (Big Circle Center)	156	213Ω

6 (Bottom Circle)	96	422Ω
7 (Big Circle Outer Ring)	127	166Ω
8 (Middle Circle Center)	150	140kΩ
9 (Middle Circle Outer)	124	320Ω

This time the display was able to light 8 of the 9 segments, at the same time, with no noticeable dimness. The one segment could dimly light up when provided power with the other segments, but would not even react when connected alone with the power supply. Based on the resistance measurements taken, the problem seems to be a connection issue as well. The sequence of lights performed correctly as shown in figure 14.

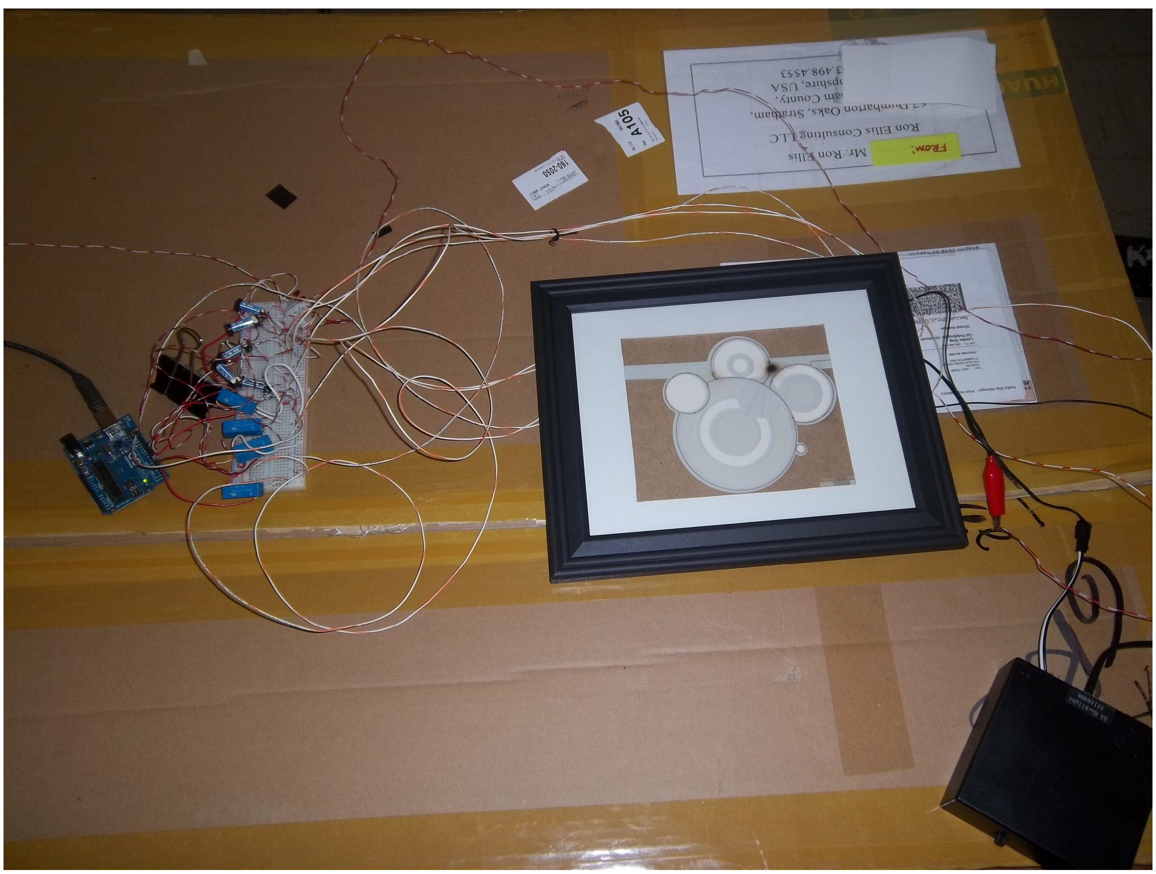

Figure 14 Final Design with Control unit to left, and Power source in bottom right

One interesting thing to note is how small, and varied are the resistances of each segment. Length of trace seemed to have no significant influence on the resistance value in the segments. Though, distance from the common does as shown in the resistance values in table 5 of the big circle center vs. outer ring, and the bottom circle vs. the tiny circle. Since these segments all had a common ground and in parallel, (excluding segment 3, which was broken), the total resistance is 47.1 ohms which, when the 80V is divided by the 47.1, the power supply is providing 1.7A to the EL display. Excluding the top circle center, the next lowest resistance segment had .482 A flowing through it, connected to a relay that was rated for .5 A. The more drastic variation in resistance could possibly come from the 1-2 um difference in dielectric, which is at an average width of 17um thickness.

Also interesting was that both power supplies were rated for 120V. Even after taking into account the meter measuring the rms voltage, they still are both less than 120V. A mere difference of 17V appeared to make a big difference in powering the display.

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Chapter 8 – Conclusion

The intent of this project was to explore 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 length of the trace in the display are important factors to consider when providing a power source. However, a secure connection between the trace and the power source is also vital.

The greatest difficulty experienced in this project resulted from having a proper connection between the silver traces and the power source due to the delicate and unique nature of a printed EL display. Solder does not adhere to the silver trace and using tape or other adhesive substances was extremely damaging to the display, as it was easily scraped off, removing the silver trace from the ITO layer.

Due to the multiple ways to construct a printed circuit, there are some recommendations that will help in future development of printed electronics. A 156tpi mesh is recommended to provide more desirable print characteristics. Also using a vacuum or inert gasses would prevent arcing. Another way to prevent arcing would be using a protective layer. Also, the preliminary test contributed to the design considerations of the graphic display in relation to silver trace lines. Finally, use a good power supply to provide enough current to the display.

The findings and recommendations from this study provide a foundation for further studies on this subject. A proposed future test is to find a more efficient and secure way of attaching the wires to the ITO film. Exploring the best way to prevent arcing to solve the problem of potential burning of the ITO could provide another test. Electroluminescent displays still have room for development and improvement. However, this study successfully identified,

explored, and provided recommendations for many of the issues facing the design of subsequent EL displays.

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APPENDIX A – ANALYSIS OF SENIOR PROJECT DESIGN

This senior project involves fabricating an interactive electroluminescent display. In selling a product, displays are important because most customers purchase a product for the first time based mainly on how the product draws customer's attention. The display's purpose is to create a point of purchase advertising that draws the customers' attention to the product advertised by the electroluminescent display over other displays in a store. The electroluminescent display has different shapes in the design that illuminate, and then fade back into the background, occurring at different intervals from each other.

The first primary constraint in the project was the limit of ITO sheets. This limited how many test copies could be produced for the project. The area of manufacture was limited as well, encompassing a maximum of 8 x 10 inches for the project, which limited the test regarding power consumption on large scale displays. Shipping times and lack of immediate access to parts presented a problem. When the power supply broke down, it took nearly a week to replace it. Radioshack could only sell relays of this magnitude in store, and was one of the few stores the even offered them. In the end they were purchased personally in stores around Long Beach and driven back to San Luis Obispo to gather enough.

The economic impacts of the creation of electroluminescent displays revolve around several categories. In terms of human capital, it will enlist more people in manufacturing of this design. With this product, graphic designers that used to do display art on corrugated, will simply switch to electroluminescent without much change in artistic tools. The corrugated industry might be affected, but there are many corrugated products being produced on a daily basis. Electroluminescent displays would take over only major displays, leaving the rest of the industry

not significantly impacted. The initial financial investment depends on whether the materials were bought in United States or imported. If imported, there is a possibility of a change in the value of the Yuan, assuming it is China, to decrease to take advantage of American purchasing. The manufacturing of the electroluminescent devices will most likely be greater than that of corrugated displays in the point of purchase area, meaning the national GDP would increase. The final effects on the environment are in terms of natural capital, where resources will have to be mined out, and the silver will not be renewable. The insulators could possibly fabricated through bioplastics, but the design for this project will not be making use of such material. Benefits of the product in terms of sales would begin after the purchase of production equipment. Additional equipment would also bring in the benefit of increased production once bought.

The immediate cost before even selling the first unit would be a designing cost. Also, there is the immediate cost of the manufacturing equipment. After that there would be the constant cost of materials, labor, and equipment maintenance in the factory. Another cost would be when machinery becomes obsolete or breaks down. The input of the electroluminescent display externally is power, but there is also a DC to AC inverter to power the LEDs. Including labor, the project would cost $14,666. However in terms of materials, and this is only as of now, it would cost $4,866 for 200 units. An EL display could probably sell for $40, which after taking into account the cost in appendix B, it would probably gain $15.07 per display for profit. If Cal Poly were to endorse this, they would profit. Or, if a company interested in producing these types of displays agrees to pay Cal Poly royalties, both the company and Cal Poly would profit from this project. The product emerge until after 30 weeks, 26 for production and an additional 4 weeks for testing, and making sure the machines, which were already bought¸ are performing correctly as well. The product will stay on the market for a year before being obsolete with

newer designs emerging. The fabrication process will be an initial expense, and maintenance cost for machinery will occur at regular intervals as well. The estimated development time currently is 26 weeks. After the project ends, the report will be archived into the library. Dr. Rong will be allowed to use this display in whatever mode she pleases.

If products were manufactured on a commercial basis, displays would probably be sold around 5,000 every 2 months, depending on how many chains buy our product and how many displays they want. Based on observations of grocery stores, there would be one type of EL display per grocery store, though it could be any store, such as Barnes and Noble, Best Buy, or even Bevmo. This value is, of course optimistic, that large, nationwide chains would want the product. Based on the number of stores in large chains, 30,000 displays would be purchased and produced a year. The manufacturing cost would be based on the assumption that a semi automated factory with 4 workers would be able to produce 400 displays in 8 hours, and that the labor would cost $10.00 per hour. In addition, the parts would cost roughly $23.00 per unit. This makes the cost per unit $24.93. The purchase price of the display would be $40. The estimated profit per year would be $930,000 per year. The cost to the user to run the device would be the electricity. Edison charges 12 cents per KWH. If this device runs on perhaps 100 Watts per hour, then supposing they run the display for the full 16 hours, then it would cost 25.6 cents per day to run [13].

Environmental impacts include toxic chemicals released into the air. These include aerosol cans used for cleaning the screens, as well as possibility of use of volatile organic compounds or VOCs for the ink design [14]. The amount of these pollutants would depend on what prevention factors we have at the factory, how thick the display is, and how fine the screen is for screen printing. Materials such as oil used to create the polymers used for insulation, as

well as the silver used for conduction are not renewable materials. There are also the materials used for ink for the display to consider. This can harm the environment when ecosystems are destroyed in order to create new mines for silver. This project could potentially harm sea animals as well if an offshore rig was to malfunction or tanker was to leak.

The difficulty with manufacturing would be to abide by the environmental laws set aside for screen printing, which is known for producing waste materials. There are generally three permits needed for usage, the Emissions Inventory Questionnaire, Operating Permit, which controls amount of Air pollutants under the Missouri Air Conservation Law, and a construction permit [14]. These rules mean that the machinery is to be designed to not cause pollutants, while still being productive enough to be competitive in the market.

Sustainability will be an interesting predicament in that, as displays, these products are only meant to last a month at most, and then discarded due to the ever-changing market with new sales and products. Maintenance should not be an issue; the products only have to last long enough for two months which will satisfy the customer. Technically sustainable polymers and ink pigments could be used. However, in the process of staying competitive, It is unlikely those would be implemented in the initial design. The conductive metal used is silver, a non renewable metal. Future upgrades would address renewable resources such as biopolymers, more power-efficient displays, and more graphical designs. The primary challenge is cost since the product needs to be competitive with other conventional displays. If electroluminescent displays would continue to evolve with the product it can attract customers over other displays.

Ethical implementations could begin with how environmental friendly the product is. The legal restraints still allows room to for the designer to decide which materials to use. Once in use, the electroluminescent display would be subject to the same ethical consequences of any

graphical art. The design could be obscene or violate laws such as indecency in public. Also, like all displays, corrugated or not, it could be used to attract minors to products such as drugs that are harmful and should not be in the hands of kids. Finally the displays could be used to advertise unsavory products such as devices related to sex.

Health and safety issues include accidentally touching solvents and getting them in a person's mouth, poisoning them. The same action can be applied to inks as well. Safety in the factory is important for concerns such as accidentally getting caught in the furnace used for curing the display. These concerns are important since they carry legal consequences such as a lawsuit by one of the workers.

In terms of social and political impacts, the design would impact international trade. Where corrugated designs require paper board, generally received from "paper farms" located in Canada, the materials required for an electroluminescent display would probably be imported from China, creating more reliance on a country that has already caused some unrest between United States exporters over the trade deficit. This product would initially be used in United States, and other countries may not support use of it, thinking it is too flashy, or is crossing the line on how far advertising should go. Marketing research would help solve this problem. The project could impact stakeholders if they think the company will flourish with this design, the stocks will increase, possibly before quarterly profits are even reported. There could be more direct stakeholders in terms of workers who may be using 401Ks in the stock market. The quarterly profits would ultimately determine whether the stakeholders will benefit or be harmed in this project. At the initial conception of design, it appears the stakeholders would benefit equally. The stakeholders would be located across the board, possibly internationally as well.

There are many new tools that have surfaced in my research of electroluminescent technology. Screen printing has been used for printed electronics for some time and has continued to advance with the ability to create electroluminescent displays. However offset lithography, commonly used for printing newspapers, and pad printing, is also used for printing labels for foods, also is used to print electroluminescent displays. Other colors besides blue are being used for electroluminescent, in particular green and red, which allows the designer to create nearly any color.

APPENDIX B – Parts List and Cost

Cost shown below is for the display with an area of $70cm^2$. Though only created 6 copies of the final design were created, with only one control relay set, since there was still a large bulk of ink, the amounts were increased for 200 units. Note that some items were not purchased in bulk, such as the Arduino Uno Boards, as well as relays and power supplies. Also this cost estimate does not include the cost in transportation of materials to production. Finally, since the dielectric, phosphor, and silver ink have coverage greater than $70cm^2$, one could produce more if not limited to amount of other components.

Additionally, there are the costs for labor. The labor costs can be divided into three areas: preparation, make-ready and production. The preparation time is the time spent to print the design onto photosensitive material, which is then used to create the emulsion, as well as cleaning the screens after production. The make-ready time is time spent printing copies of the screen to check for errors such as registration between the different layers of the EL display. The production time would be the time taken to print the layers, drying time, as well as the assembly of controls, assuming that the relays would be soldered by machine. This process would probably require 2 people on assembly, connecting the controls and power, and two for printing for all 4 layers. It would take 1.5 hours for preparation, 30 minutes for make-ready, and 2 hours for production. It is important to note that while production time would increase, so long as the same design is used, the make-ready and preparation time would remain the same. Excluding development cost, the cost of an individual display would be $24.93.

Also the A# listed for ITO and Power supply correlate to the area of the sheet. For instance, an A4 sheet is the sheet of a paper, while A5 is half that size. Though the power supply is rated for A5 sheet, not A4, the phosphor used on the sheet was less than half of the A4 sheet, so the A5 power supply was sufficient to run.

Item	Cost	Additional Info
200 grams of EL dielectric white ink	$82[19]	Purchased from Gwent Group, rated to cover 260cm^2 for 2 layers per gram[22]
200 grams of EL Ag Flex 58.85% ink	$360[19]	Purchased from Gwent Group, rated to cover 165cm^2 per gram[20]
200 sheets of ITO polyester size A4	$120[19]	Purchased from Gwent Group size A4[21] .
200 grams of phosphor Blue	$284[19]	Purchased from Gwent Group, rated to cover 120cm^2 per gram[23]
200 Arduino Uno Boards	$400	Used to run code sending signals to the relays when to turn on and off the lights. The board was purchased for $20 each from IEEE.
900 125 V AC Relays	$2700	The relays are needed to direct the high voltage to the proper conductive lines, each cost $3 from Radioshack.
200 A5 backlight 110-120V 50-60 Hz power supplies.	$800	Purchased at $40 per piece at Amazon.com
Labor Cost	$240	Cost of Screen Printing 200 at $10 per hour.
Development Cost	$9,800	Worst Case: 24 weeks, Best case: 10 weeks, Average: 16 weeks (10 + 4(16) + 24)/6 = 16.333 weeks at 15 hours per week = 245 x $40/hr.

Total Cost: $14,786 (4,986 excluding development cost)

Table 6: Cost Estimation

APPENDIX C – Schedule and Time Estimates

As time progressed through the project, the schedule changed to reflect situations that could not be predicted earlier. These changes included a switch in partners, broken parts, or delays in components arriving. However this had been expected, which is why the projected Gantt chart was made to expect the project to be finished early in the Spring Quarter.

Projected Gantt Chart

Task Name	Start	Finish	Time	9/19/11	10/31/11	12/5/11	1/2/12	1/23/12	1/30/12	2/27/12	4/16/12	5/7/12
1: Project Plan	9/19/11	12/5/11	11w									
2: Meet with group member, share ideas for design.	10/31/11	5/7/12	158d									
3: Build Sequence 1	1/2/12	4/16/12	15 w									
3.1: Design for Circuitry (Design for Silver)	1/2/12	1/23/12	3w									
3.2: Purchase Components	1/23/12	1/30/12	1w									
3.3: Construct & Test Circuits	1/30/12	2/27/12	4w									
3.4: System Integration and Test	2/27/12	4/16/12	7w									
4: Alternate Build Sequence	1/2/12	4/16/12	15w									
4.1: Dielectric (Design for Carbon)	1/2/12	1/23/12	3w									
4.2: Purchase Components	1/23/12	1/30/12	1w									
4.3: Construct & Test Circuits	1/30/12	2/27/12	4w									
4.4: System Integration and Test	2/27/12	4/16/12	7w									
5. Interim Report	10/31/11	2/27/12	18w									
6. Final Report	2/27/12	5/7/12	15w									

Figure 15: Projected Gantt Chart

Actual Gantt Chart

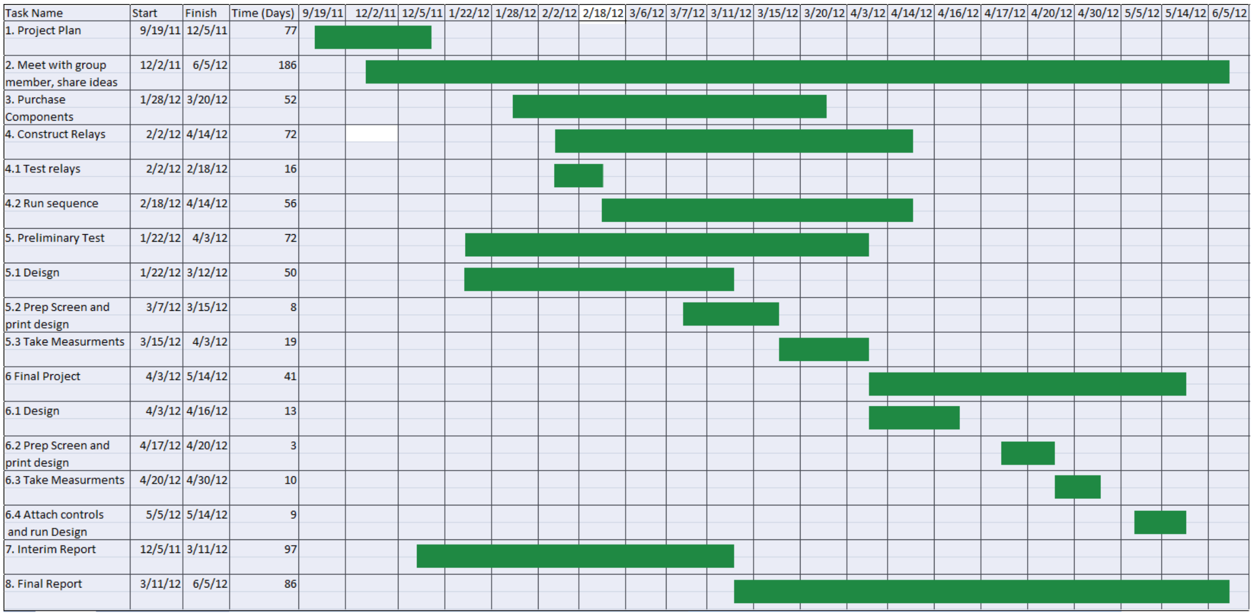
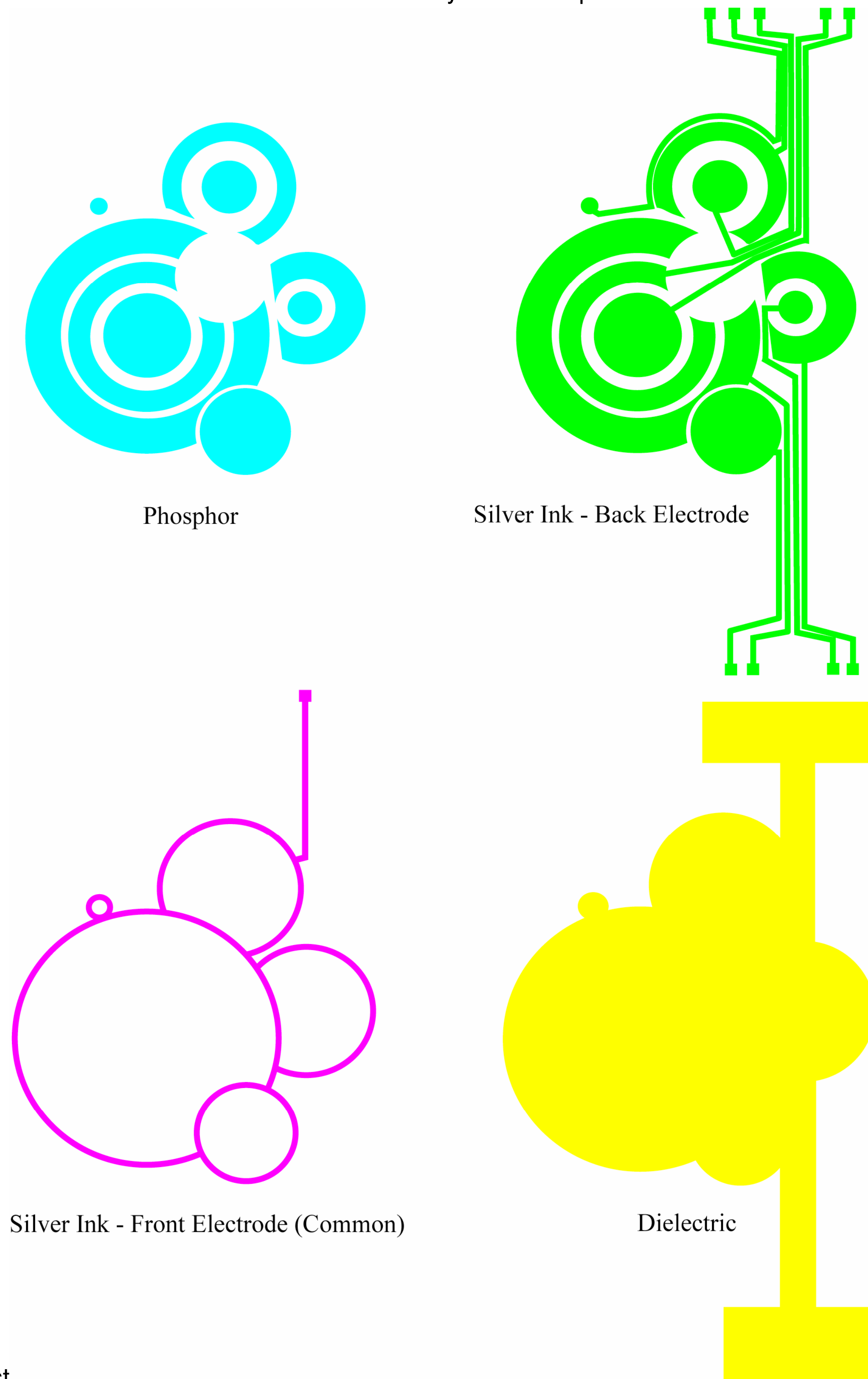


Figure 16 Actual Gantt Chart as of 5/23/2012

APPENDIX D – Ink Layers for Graphics



Test

Figure 17 Ink Layers

APPENDIX E –Relay Test Code

```
//Sequence code for nine relays
//assign relay numbers:
const int relayOne = 2;
const int relayTwo = 3;
const int relayThree = 4;
const int relayFour = 5;
const int relayFive = 6;
const int relaySix = 7;
const int relaySeven = 8;
const int relayEight = 9;
const int relayNine = 10;

void setup() {
  //initialize the relay as an output:
  pinMode(relayOne, OUTPUT);
  pinMode(relayTwo, OUTPUT);
  pinMode(relayThree, OUTPUT);
  pinMode(relayFour, OUTPUT);
  pinMode(relayFive, OUTPUT);
  pinMode(relaySix, OUTPUT);
  pinMode(relaySeven, OUTPUT);
  pinMode(relayEight, OUTPUT);
  pinMode(relayNine, OUTPUT);
}

void loop(){
  digitalWrite(relayOne, HIGH);
  //Big circle outer line
  delay (1000);
  digitalWrite(relaySeven, HIGH);
  //big circle middle line
  delay (1000);
  digitalWrite(relayNine, HIGH);
  //big circle center
  delay (1000);
  digitalWrite(relaySix, HIGH);
  //tiny circle
  delay (1000);
  digitalWrite(relayEight, HIGH);
  //top circle outer line
  digitalWrite(relayFour, HIGH);
  //Top circle center (broken)
```

```
  delay (1000);
  digitalWrite(relayThree, HIGH);
  //Middle Circle outer line
  delay (1000);
  digitalWrite(relayFive, HIGH);
  //Middle Circle center
  delay (1000);
  digitalWrite(relayTwo, HIGH);
  //Solid Bottom Circle
  delay (1000);
  digitalWrite(relayNine, LOW);
  delay (1000);
  digitalWrite(relaySeven, LOW);
  delay (1000);
  digitalWrite(relayOne, LOW);
  delay (1000);
  digitalWrite(relaySix, LOW);
  delay (1000);
  digitalWrite(relayTwo, LOW);
  delay (1000);
  digitalWrite(relayFour, LOW);
  digitalWrite(relayFive, LOW);
  delay (1000);
  digitalWrite(relayThree, LOW);
  delay (1000);
  digitalWrite(relayEight, LOW);
  delay (1000);
}
```