OLED Screen Investigation and Evaluation

CSC 461 Group Project Report

Nathan Harmsworth
Liam Day
Jianzhao Liu
Saige Liu
The JSNL Team: feliceliu123@gmail.com

Table of Content

1. Introduction

Multimedia is a diverse subject concerning the implementations required to display media. Video screens are one of the main ways of displaying picture and video. Over the years a variety of technologies have been employed from CRT to the futuristic MicroLED.

We are doing our project on Organic Light Emitting Diode (OLED). Ever since OLED was invented, it has been gradually taking over LCD to dominate the display screen market. Today, OLED has become one of the major multimedia displays used. OLED features high definition, long life, and low energy consumption. These traits make OLED an ecologically friendly choice. In this project, we will study the OLED screen and analyze its strengths and weaknesses.

The main topics we will be focusing on will be; the design of OLED, the input/output of OLED, technologies that use OLED, and the differences between OLED and other types of popular displays. In order to learn about OLED, our team has been surveying this topic.

2. Articulation Work

In order to aid in the success of our project, we underwent some basic articulation work. Our team employed Asana in order to coordinate tasks. We used Wordpress to report on our project. Facebook messenger was used for communication and general team building. We deployed a small web app to illustrate a concept and deployed it through Heroku. Finally, we made use of Google Docs for versioning and file storage.

2.1 Expected deliverables and weekly schedule

Figure 1 shows the full weekly schedule for our group project.

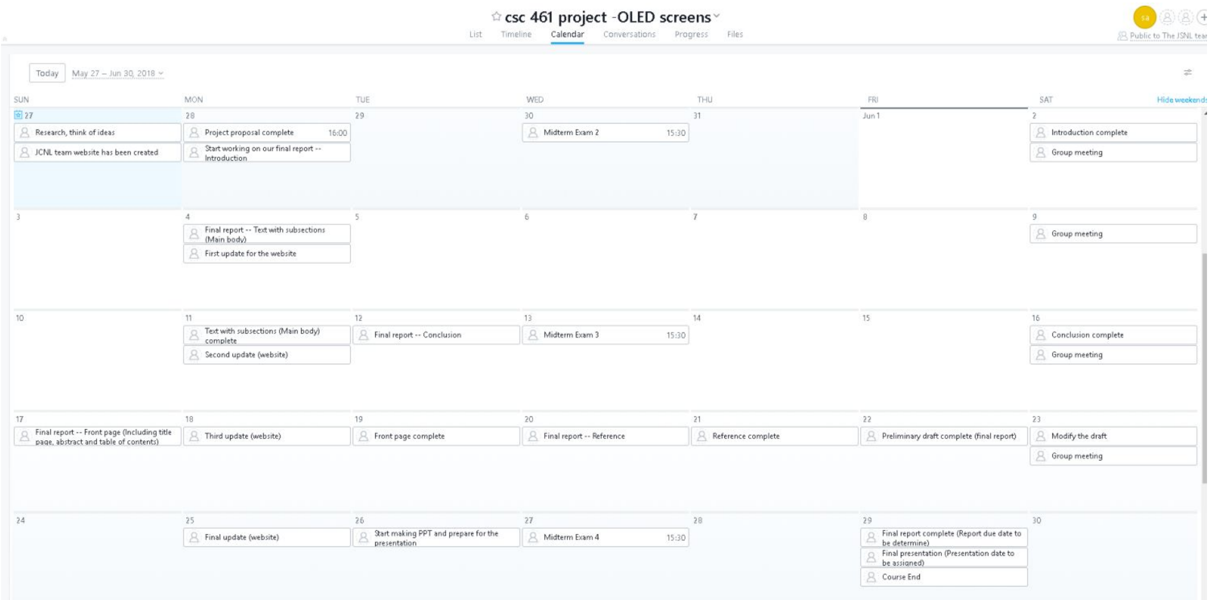

Figure 1. Weekly Schedule

2.2 Website

Here is the weekly updated project website: https://thejsnlteam.wordpress.com/

We used our website for some blog posts about group activities. Our group ended up strongly preferring google docs for content management. This has the limitation of lowering our works visibility.

3. OLED Structure

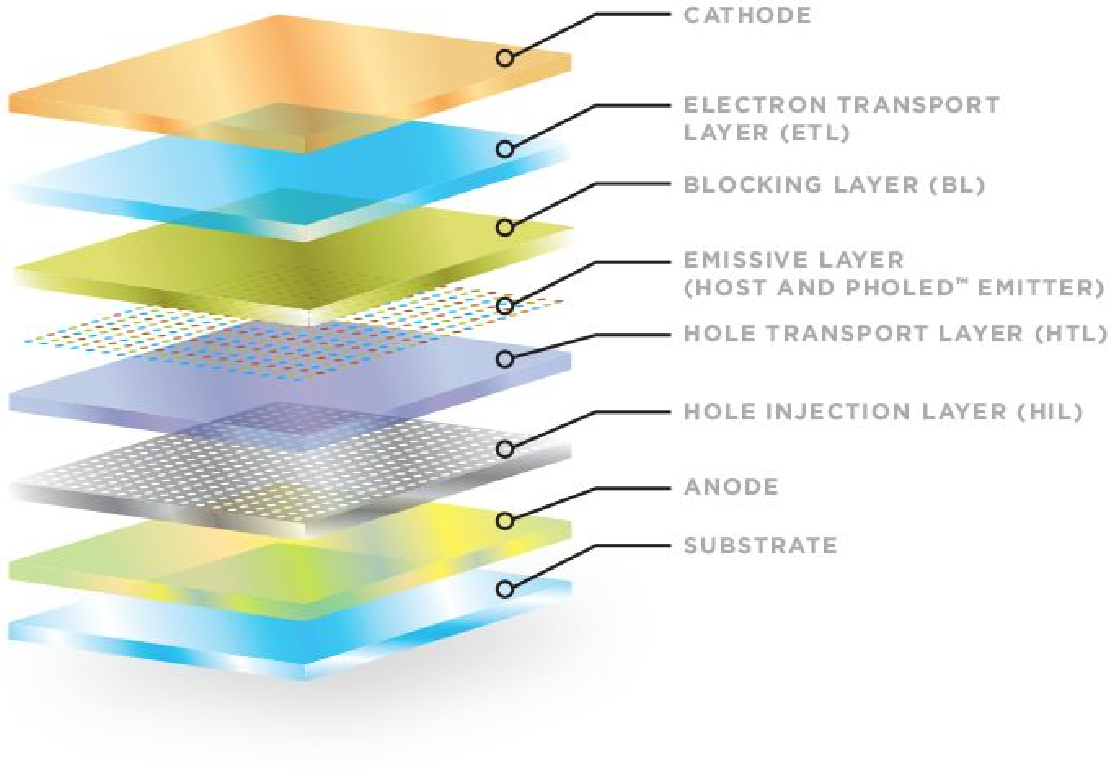

Figure 2. Best Oled manufacturer[1]

OLED is made of emissive electroluminescent crystals, which are materials which emit light when a current is applied, this is the foundation of OLED technology. From the diagram above, there are eight main components in an OLED. In the following section, we explain the definition and usage of each component one by one. [2]

3.1 Components

3.1.1 Cathode

The component through which electrons enter the OLED, it is negatively charged. It is generally seen as the opposite of the anode.

3.1.2 Electron Transport Layer

Allows electrons to propagate through from the cathode.

3.1.3 Blocking Layer

Limits flow of electrons and helps prevent electrons from leaking.

3.1.4 Emissive Layer

Holes and electrons meet in this layer releasing light photons. Leaking refers to unwanted recombination of holes and electrons outside the emissive layer.

3.1.5 Hole Transport Layer(HTL)

Moves the holes through the OLED in a way that prevents them from leaking.

3.1.6 Hole Injection Layer(HIL)

Allows holes, or absence of electrons to propagate through from the anode.

3.1.7 Anode

The component through which electrons leave the OLED, it is negatively charged. It is generally seen as the opposite of the cathode.

3.1.8 Substrate

A solid surface on which electronic components can be deposited. Acts as support for the device. The substrate could be plastic, glass or metal.

Those are the eight basic components and layers in OLED, OLED also have several different variations.

3.2 OLED Variations

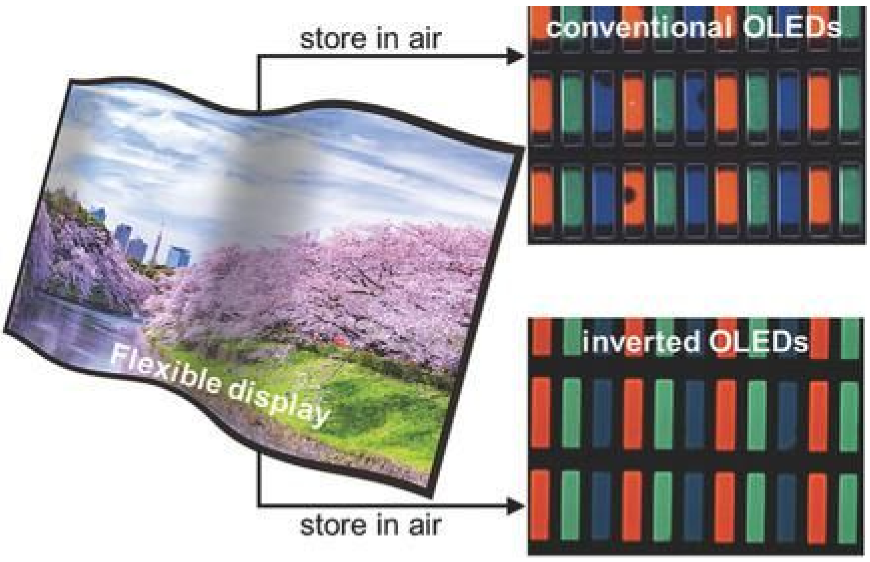

Figure 3. Two variants of OLED screens [3]

3.2.1 Bottom Emission

Bottom emission OLED devices are devices where the light emitted passes through the transparent bottom electrode as well as the substrate that the panel was created on. AMOLED are typically created with a non-transparent bottom substrate, leading to light being blocked if the device is bottom emission.

3.2.2 Top Emission

Top emission OLED devices are devices where the light emitted exits through a lid that is added after creating the device. These top emission OLED devices are better for AMOLED due to the non-transparent substrate used under most AMOLED panels.

3.2.3 Transparent OLED

Transparent OLED devices are made by using a transparent substrate on both the top and bottom sides of an OLED device. This allows the device to have both the bottom and top emission properties. This type of OLED is typically used in Heads-up Displays and augmented reality applications.

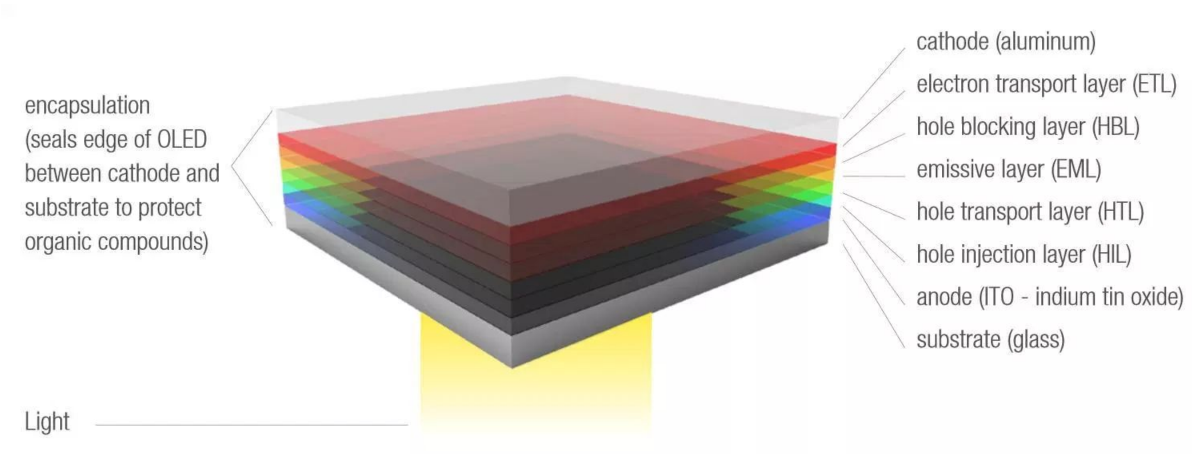

Figure 4. Layers of Transparent OLED [4]

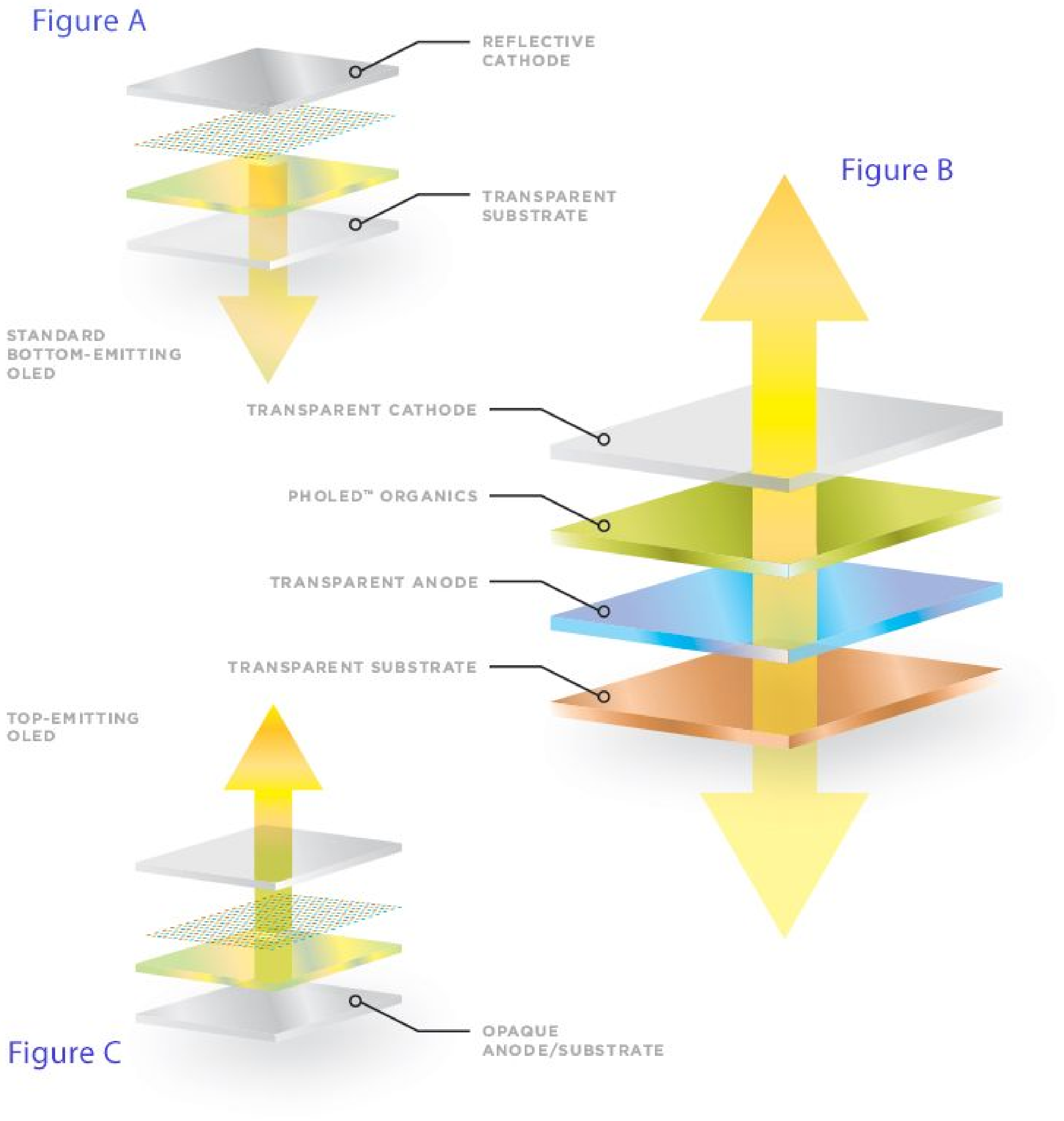

Figure 5. Layers of three different variants of OLED [5]

3.2.4 Stacked OLED

Stacking the red, green, and blue sub-pixels instead of placing them side by side creates what is known as stacked OLED. This leads to a higher color depth and reduced gaps between pixels.

3.2.5 Inverted OLED

Inverted OLED places the cathode on the bottom attached to the substrate. This design is an attempt to lower the cost of OLED by making use of amorphous silicon and a TFT, this is a type of switch.

4. OLED Fabrication

In this section, we are going to introduce two manufacturing methodologies of OLED.

4.1 Organic Vapor Phase Deposition

Organic Vapor Phase Deposition is a process in which thermal vaporization is used to deposit material on a substrate. Thermal vaporization helps a material reach a substrate with very little collisions with the gas molecules in the space between the source and the substrate.

Using a vacuum environment reduces the gaseous contaminants in the process to a much lower level. This clean environment is part of the reason OLED manufacturing has improved. The vacuum also helps reduce environmental factors in the process.

The thermal evaporation itself is usually done by using thermally heated tungsten wire coils or a high energy electron beam. One of the biggest advantages of this process is that it does not require chemical processing, the material is simply deposited. This means that chemical damage to the emitting region can be avoided.

4.2 Inkjet Printing

Older OLED production methods use a process called “Shadow Masking” in which the organic materials are deposited onto a glass sheet through a thin metal stencil. This process has problems as organic material is wasted when it is deposited on the stencil. By using inkjet printing, the organic materials can be precisely deposited so less organic materials are wasted. This technology has finally become commercial this year, as some difficulties had to be solved before this process could become financially viable for OLED producers. The three biggest issues are all related to the accuracy of inkjet printers. The pixels that are to be printed on are very small and the inkjet needs to be able to make sure that the organic material will be printed on the correct spot. The second issue is that the correct number of drops of organic materials need to be placed into the pixels. Finally, the ink needs to dry and deliver flat films of materials. In June of 2018, a Japanese company by the name of JOLED announced that they began developing a production plant with inkjet printing. Below is an image of the inkjet printers they have designed.

Figure 6. A Kateeva OLED ink-jet printing system [6]

The advantage of inkjet printing is that it allows OLEDs to be made in big size at a reduced cost. It is using a non-contact deposition so that the contamination is reduced. Furthermore, inkjet printing makes manufacturing flexible substrates possible. However, there are still some cons of inkjet printing. When building small molecule layers, there might be problems with pinholes. So that factory can only use evaporative technology to build small molecule layers. [7]

5. OLED Control

In this section, we explore OLED on its control methods. Generally, to make an OLED emit light, the controller applies a voltage across the OLED. Electrons enter through the Cathode and holes, the absence of electrons, become prevalent in the Anode. This transmits to the Emissive Layer and the holes and electrons meet. As the meeting of electrons and holes occurs, photons are released creating visible light. This process is completed row * column times across OLED screens as each pixel is a single OLED. [8]

5.1 Demonstration

We have a demo of the different OLED control schemes available in an online web application. The application is hosted through Heroku and demonstrates PMOLED and AMOLED in a visual way. Use the AMOLED and PMOLED buttons to select the mode it is running in and the Set Delay in order to change the refresh rate. The patterns displayed are the numbers 1-9 as would be seen on a digital clock, the current number can be seen in Current State. The line being refreshed is visible under Current Line.

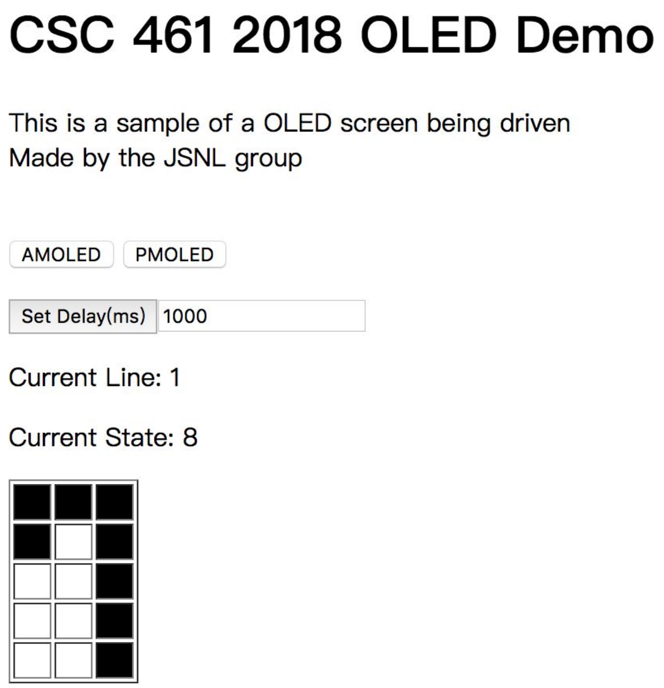

Figure 7. Screenshot of the OLED control methods demonstration.

For further exploration on the demonstration, check on the following website: https://csc461.herokuapp.com/

5.2 PMOLED

Passive-Matrix OLED (PMOLED) is one of the ways in which OLED screens are controlled. The original way of controlling OLED screens was PMOLED in part due to its simplicity. Good contrast with deep blacks is one of the highlights of OLED technology and it is prevalent in PMOLED. The PMOLED display operates by writing one row of pixels at a time. PMOLED is Passive-Matrix because only one line of pixels is ON at any time. The lines are refreshed at a high frequency in order to trick the human eye into thinking the entire screen is lit.

Unfortunately, if the lines are driven at a normal light level the average light given off by the screen will be (Light of Single Row)/(Number of Rows). In order to make PMOLED screens bright enough the single lines need to be driven with much more voltage so their average light is on par with other screens. This method has two big problems: the high voltage causes a lower lifespan and the power consumption is increased. These problems are negligible at small screen sizes as the amount of voltage needed to drive each line is based on the total number of lines. A rough estimate for the maximum allowable screen size would be 200*200 [9]. At this point in time, the main reason to use PMOLED would be its low cost due to its easy production [10].

AMOLED is also associated with an addressing scheme. For a rows * columns display, to address the display rows + columns unique addresses are used. The row is selected with signal Vr and columns are selected individually with Vc in order to turn pixels on. Color PMOLED works similarly, but there are more OLED in a single pixel leading to wider rows.

Figure 8. PMOLED in Color [11]

5.3 AMOLED

AMOLED was created after PMOLED in order to solve some of the issues around PMOLED. AMOLED differs from PMOLED in that each diode is connected to a transistor and a capacitor. This technology allows AMOLED to have memory to maintain its state while other diodes are being addressed. These changes lower the amount of voltage required to drive the diodes increasing the lifespan and energy efficiency. Addressing is done in much the same way as PMOLED with Row +

Column unique addresses. AMOLED was invented by Bernard J Lechner while at RCA around 1968 [12]

6. OLED Implementations

The implementation of OLED is growing rapidly around the world. Ever since OLED had been invented, it is a hot topic in the display market and hot research topic in display companies such as Samsung, LG, Sony and so on. The main implementation of OLED is introduced in this section.

6.1 Smartphone

There are several screen technologies currently in use today, and each smartphone manufacturer has its own preferences and tastes for their devices. The OLED display has an advantage that places it above the rest, especially compared to its current main competitor, LCD.

Mobile phones that have OLED screens are rapidly becoming more prevalent, with an estimated 250 million AMOLED screens produced in 2015 - mostly to satisfy demand from mobile phones. Samsung has been using AMOLED in its high-end phones for many years, and most phone makers are also starting to adopt OLED displays (including Apple, according to reports, in 2017).

When implemented OLED on high-resolution smartphones, each pixel contains red, green and blue OLED subpixels as shown in Figure 9.

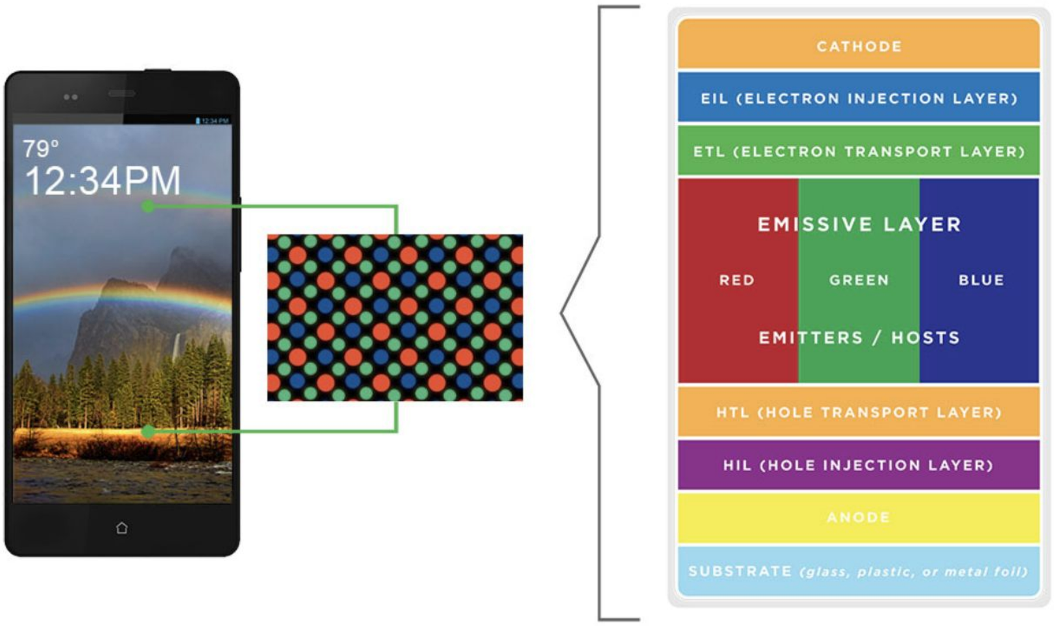

Figure 9. RGB OLED side by side [1]

6.2 Television

Companies such as LG, Samsung, Sony, and Panasonic all have OLED televisions on the market. They are considered to be higher quality than the LCD televisions and have a higher price point to reflect the difference in quality. As OLED production becomes faster and less expensive, the prices of the OLED televisions on the market will also decrease until one day they become as affordable as LCD is today. Different from deploying OLED on mobile phones, when using OLED on televisions, the method is to generate white light in each pixel and then use a color filter to get red, green, and blue subpixels as shown in Figure 10.

Figure 10. White OLED with Color Filter [1]

6.3 Heads-Up Display

Heads-Up Display, referred to as HUD, was first introduced in the 1940's to help fighter pilots during the war. HUD is now being used in other vehicles and there is experimentation of using HUD on glasses and scuba goggles. OLED is most commonly used for the pixels of the HUD. One of the biggest issues with HUD is that you need the display to be transparent when pixels are not producing light. When turned off, transparent OLEDs are up to 85% as transparent as their substrates, which makes them perfect for HUD.

Figure 11. Qwiic Transparent OLED screen meant for custom HUD application [13]

7. Comparisons

OLED screens are known mostly for their high contrast and brightness. However, one of OLED's biggest weaknesses is its short lifespan due to the blue pixels having a much shorter operating lifetime [14]. Based on these factors, our team compared three other modern display screens to OLED on brightness, contrast, lifespan, burn-in, cost, power consumption and viewing angle in this section. Those screens are plasma, LED-LCD, and MicroLED.

7.1 Comparison with Plasma

Plasma screens first became commercial products in 1997 and were discontinued in 2013. Since OLED screens first appeared on the markets in 2008, the OLED screens are considered superior to the plasma screens. The first major difference is the resolution quality. Plasma screens can’t reach 1080p or 4k resolution whereas OLED screens can, which quickly became a bigger issue as video and image quality continued to improve. OLED screens also have a higher brightness which creates a larger contrast. Contrast is extremely important as it is more noticeable to the human eye than color and even resolution. Plasma screens use more electricity than OLED screens of the same size, and also need to be much thicker than the OLED screens. However, not everything about the plasma screen is worse than the much newer OLED technology, as plasma has a much longer lifespan as well as being the less expensive option. [15]

7.2 Comparison with LCD

LED-LCD screens, more commonly known as just LCD screens, are considered to be the standard for commercial screens available today. They overtook plasma screens in the year 2007 and are now competing with OLED and microLED for screen options. LCD screens can reach the same resolution as OLED screens but is considered to be lower quality than OLED. The main reasons that LCD screens are lower quality are due to the LED backlight that is used to illuminate the crystals that produce colors. Since each pixel in OLED screens produces their own light, they can produce darker shades of black than LCD screens can, which creates a higher contrast.[16] Another thing that LCD screens suffer from is uniform contrast, which is how consistent the brightness is across the entire screen. Viewing an LCD screen from any angle that is not straight on noticeably lowers the quality of that screen whereas OLED screens do not reduce quality based on viewing angle. The lower brightness of LCD screens uses less energy than OLED screens and also leads to a longer lifespan than OLED screens. The prices on OLED screens is much higher than that of LCD screens, which is one of the main reasons that OLED has not fully taken over the commercial screen market. [17]

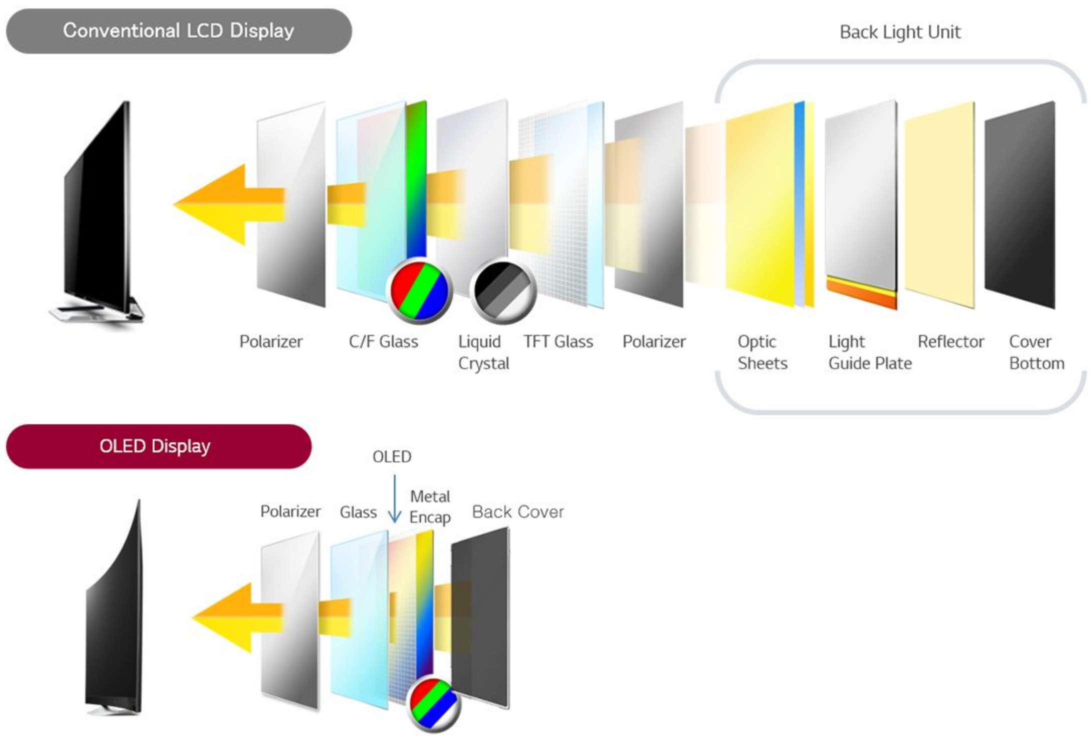

Figure 12. LCD Display Vs OLED Display [18]

7.3 Comparison with MicroLED

MicroLED screens are a very new technology, with commercial screens appearing on the market for the first time this year. These new screens are the only ones that can emit a higher brightness than OLED screens can and are also more energy efficient. Despite the higher brightness microLED has a longer lifespan than both OLED and LCD screens do. OLED has less flexibility in the sizes available whereas MicroLED can be fit to any size that is needed. One thing that all other screens have in common is burn-in, it occurs when an image is displayed on a screen for too long and causes the next image to retain part of the previous one. MicroLED does not have any chance of burn-in. The viewing angles on MicroLED are slightly better than OLED as well. The drawback of Micro LED screens is in the form of production. Each pixel has to be made and carefully placed individually making the process expensive and time-consuming. OLED screens can be produced much faster, which means that they are available for much lower prices than any micro LED screens.

7.4 Comparison Table

Based on the discussion above, we created the comparison table below listing OLED, Plasma, LCD and MicroLED's attributes. OLED is much more superior than Plasma except the short lifetime issue. While LCD has a lower power consumption but a narrower viewing angle compared to OLED. MicroLED is the next generation of display technology and it has a better performance, wider viewing angle and longer lifespan, the only defect is the high manufacturing cost.

Comparison to OLED	**Plasma**	**LCD**	**MicroLED**
Brightness	Lower brightness	Lower brightness	Higher brightness
Contrast	Lower contrast	Lower contrast	Higher contrast
Lifespan	Higher	Higher	Much higher
Burn in	Higher chance	Same chance	Much lower chance
Cost	Much lower	Lower	Higher

Power Consumption	Higher	Lower	Lower
Viewing Angle	Same	Much lower	Wider

7.5 The Lifetime Issue of OLED

From the comparisons, we found out that the short lifespan of OLED is the major issue. Actually, scientists have found the reason for it. Among red, yellow, green and blue OLED emitters in OLED, the blue emitter is the most fragile one. On the phosphorescent blue emitter, the short lifespan has become even more extreme. As shown in Figure 13, the blue PHOLED only have 600 hours of operation lifetime before the luminance decayed to 95%, while only 20000 hours before it decreased to 50% compared to the initial level. These two data is much smaller than Green, red, green-yellow PHOLED's testing result.

PHOLED Performance (at 1000 cd/m²)	*1931 CIE Color Coordinates*	*Luminous Efficiency (cd/A)*	*Operating Lifetime (hrs)*	
			LT 95%	*LT 50%*
DEEP RED	(0.69, 0.31)	17	14,000	250,000
RED	(0.66, 0.34)	24	25,000	600,000
RED	(0.64, 0.36)	30	50,000	900,000
GREEN-YELLOW	(0.46, 0.53)	72	70,000	1,400,000
GREEN	(0.34, 0.62)	78	18,000	400,000
LIGHT BLUE	(0.18, 0.42)	47	600	20,000

Figure 13. UDC OLED material performance, 2011 [19]

In 2016, LG had announced that they have developed a type of OLED TV that has a 100000 hours lifespan [20]. LG's OLED TVs have secret white pixels that help to pass light through filters. This technology can increase the lifetime and lower the cost. This could one approach to solve the lifetime issue.

In 2018, a bunch of Samsung Electronics researchers studied on the blue emitters' lifetime problem and found a new mechanism for degrading the blue phosphorescent organic light emitting device [21]. The technology behind is called emitting layers with the exciton-induced generation of polaron pair. They found that electron transfer from dopant to host excitons generate radical ion pairs. The study result showed the devices' lifetimes are linear with radical ion pairs' annihilation rate. Their research results show the significance of exciton-induced electron control and give a new way to design new materials for longer lasting lifetime blue phosphorescent devices. The next step will be using the new approach to manufacture a new commercial material to build the blue phosphorescent emitters. There is a great chance that the short lifetime issue of OLED will be resolved in the near future.

8. Conclusions

OLED and other screen technologies act as a key component of multimedia. Our project on OLED has delved into the creation and use of OLED as well as the various designs used. Our explorations into OLED have revealed it to be a very powerful display technology. It is very pleasing to the eye with great brightness and color contrast at a reasonable price. OLED is unfortunately held back by its lifespan. The lifespan and cost of OLED continue to improve as materials and manufacturing methods improve. With advances to OLED, we assume that OLED will become the center of the display market in the coming years.

9. Member Contribution

Nathan Harmsworth

Nathan focused primarily on the applications of OLED and the differences between OLED and other types of displays. This included researching the productions methods of OLED, consumer ratings, and the implementations of OLED. Nathan also formatted and edited the report.

Liam Day

Focussed on researching OLED functionality. Wrote up the areas of the report concerning how OLED worked. Wrote web demo. Studied OLED structure. Participated on forum in order to help others understand our project. I really enjoyed working with this group and believe everyone contributed and worked effectively.

Jianzhao Liu

- Preparing the script and the powerpoint for the presentation.
- Build up weekly timetable.
- Research on optical characterization of OLED display and OLED material
- Update the project website

Saige Liu

As the team leader, Saige is responsible for connecting team members with instructors. She is the main contact of the project. Saige contributed in research on the technologies behind OLED, studied on the reason and resolution of OLED short lifespan issue and devoted in presentation and research report. She maintained and updated the project website, formulated and organized the video presentation with scripts and slides. She passionately participated in group discussion and report writing and formatting.

10. References

1. "Organic Light Emitting Diodes (OLEDs)." *Universal Display Corporation*, oled.com/oleds/.
2. Freudenrich, Craig. "How OLEDs Work." *HowStuffWorks*, HowStuffWorks, 24 Mar. 2005, electronics.howstuffworks.com/oled1.htm.
3. Fukagawa, Hirohiko, et al. "Long-Lived Flexible Displays Employing Efficient and Stable Inverted Organic Light-Emitting Diodes." *Advanced Materials*, 2018, p. 1706768., doi:10.1002/adma.201706768.
4. "For the Love of Contrast // Part 1: The OLED Explained." *Columbia Science Review*, 1 Nov. 2017, columbiasciencereview.com/2017/03/31/for-the-love-of-contrast-part-1-the-oled-explained/.
5. "Transparent OLEDs (TOLEDs)." *Universal Display Corporation*, oled.com/oleds/transparent-oleds-toleds/.
6. "OLED Ink Jet Printing: Introduction and Market Status." *IHS - Page 1 | OLED-Info*, OLED-Info, www.oled-info.com/oled-inkjet-printing.

7. A. Islam, M. Rabbani, M. H. Bappy, M. A. R. Miah and N. Sakib, "A review on fabrication process of organic light emitting diodes," *2013 International Conference on Informatics, Electronics and Vision (ICIEV)*, Dhaka, 2013, pp. 1-5. doi: 10.1109/ICIEV.2013.6572656
8. "How OLEDs (Organic LEDs) Work." *Explain That Stuff*, 1 Nov. 2017, www.explainthatstuff.com/how-oleds-and-leps-work.html.
9. Charbax. "OLED-Info Talks Visionox PMOLED vs AMOLED." *YouTube*, YouTube, 10 June 2018, www.youtube.com/watch?v=ADf4rYAiVVc.
10. "PMOLED vs AMOLED - What's the Difference?" *IHS - Page 1 | OLED-Info*, OLED-Info, www.oled-info.com/pmoled-vs-amoled-whats-difference.
11. "PMOLED - Crystalfontz LCD Glossary." *Crystalfontz.com*, www.crystalfontz.com/blog/glossary/pmoled/.
12. Lechner, Bernard. "History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for Television at RCA in the 1960s" *Information Display*, Jan. 2008, pp. 26-30.
13. "Qwiic Transparent OLED HUD." *SEN-13266 - SparkFun Electronics*, www.sparkfun.com/products/14691.
14. "OLED Lifetime: Introduction and Market Status." *IHS - Page 1 | OLED-Info*, OLED-Info, www.oled-info.com/lifetime.
15. Morrison, Geoffrey. "LED LCD vs. OLED vs. Plasma." *CNET*, CNET, 18 Nov. 2013, www.cnet.com/news/led-lcd-vs-oled-vs-plasma/.
16. Morrison, Geoffrey. "What Is TV Contrast Ratio?" *CNET*, CNET, 19 Mar. 2015, www.cnet.com/news/what-is-contrast-ratio/.

17. Morrison, Geoffrey. “LED LCD vs. OLED: TV Display Technologies Compared.” *CNET*, CNET, 12 Apr. 2017, www.cnet.com/how-to/led-lcd-vs-oled/.
18. “OLED | Technology & Solution | Information Display | Business | LG Global.” *LG Smart Watch Style in Titanium(W270) With Android Wear 2.0 | LG USA*, www.lg.com/global/business/information-display/technology-solution/oled.
19. Mertens, Ron. “UDC PHOLED Material Performance Update - Green Now Reaches 1.4 Million Hours.” *IHS - Page 1 | OLED-Info*, OLED-Info, 4 May 2017, www.oled-info.com/udc-pholed-material-performance-update-green-now-reaches-14-million-hours.
20. Rasmus, Larsen.“An Introduction to MicroLED” *a New Self-Emitting Display Technology - FlatpanelsHD*, 7 Jun 2016, www.flatpanelshd.com/news.php?id=1465304750.
21. Kim, Sinheui, et al. “Degradation of Blue-Phosphorescent Organic Light-Emitting Devices Involves Exciton-Induced Generation of Polaron Pair within Emitting Layers.” *Nature Communications*, vol. 9, no. 1, 2018, doi:10.1038/s41467-018-03602-4.