Section 3 - Review of State of the Art

Q1) Introduction

In our ever increasing technological society, many of us are already familiar with displays that come in many different shapes, sizes and forms (McDonald 2020). Display technologies are surfaces that output graphical images, texts and videos to billions of people around the world. Display technologies are constantly improving, a decade ago the battle of display supremacy was between LCD and plasma screens (McDonald 2020).

Nowadays, OLED is dominating the market share with its high-resolution images on thin screens with an almost infinite range of deep blacks and high-quality contrasts (Katzmaier 2020). It is used on millions of devices such as TVs, smartphones, and computer monitors, with LG being the primary supplier (Kanter 2020). However, there have been major issues with price, brightness, colour loss over time, size variability, burn-in and slow rates of advancements, which has put its hold over future markets into question (Bolton 2020).

In the last few years, Samsung has unveiled a new kind of display technology called QLED. It is already considered to be an upgrade of LCD (which has a big market share) by many, but although it may not currently be as popular as OLED, its future is looking promising (Kanter 2020). For example, just earlier this year, Samsung unveiled its new state of the art Q800T 8K Smart TV, and its reviews have been outstanding.

Q2) History

1890s: Invention of CRT

The origins of display technologies, begins with Karl Braun's invention of Cathode-Ray Tube (CRT) in 1897. It displays images via use of electron guns and a phosphorescent screen. It kickstarts the display technology revolution that sets the foundation for early TVs and computer monitors (Walden, 2020) in the 20th century. Interestingly, JJ Thomson used the CRT to discover the existence of the electron.

1910s: Discovery of Electroluminescence

In 1907, Henry Round discovers a natural phenomena, where when a semiconductor material is passed through a electric field, light is emitted (Walden, 2020). This sets the groundwork for which LED technology will arise from (Center, 2020).

1920s: Invention of Mechanical TV and Introduction of Colour TV

In 1924 John Logie invented first mechanical television which transmitted objects in motion (Walden, 2020), as well as publicly demonstrating the first colour television in 1928. This demonstrated the power and future potential of television to the world (Baird, 2020).

1940s: Invention of 3D Movies

In 1947, the Soviet Union releases the first 3D movie, however due its poor quality, the concept did not become popular till many years later (Walden, 2020).

1950s: Invention of Curved Screens and Introduction of Colour TVs

In 1952 curved screens were used in some movie theatres across the United States, but failed to make an impact. In 1953 television begin introduce colour displays although the trend only catches on in 1970s. (Walden, 2020)

Early 1960s: Invention of LED (mash)

In 1961 Robert Biard and Gary Pittman invents the first LED lights but its invisible to the human eye. A year later, Nick Holonyack invents the visible LED lights (Walden, 2020).

Mid 1960s: Invention of LCD, Plasma screen and Touchscreen
In 1964, James Fergason invents LCD and Plasma screens (Konica), this allows for flat-screens to be made. Then in 1965, E.A. Johnson a device that is widely regard as the first touchscreen display which is later adapted to ticketing kiosks and ATMs (Walden, 2020).

Late 1960s: Invention of HDTV, IMAX and VR
After the 1964 Tokyo Olympics, experimentation leads to birth of HDTV in Japan, although not reaching the US till the 1990s. Then in 1967, IMAX is conceived by Canadian filmmakers, the first large display screen experience available. In 1968, Ivan Sutherland and Bob Sproull invent the virtual reality headset although it didn't become popular till the 1990s (Walden, 2020).

1970s:
In 1977, Apple releases the Apple II computer, which is the "first PC with color graphics" (Staff 2020).

1980s: Invention of OLED
In 1987, computer scientists at Kodak, invent the first OLED (Walden, 2020). Again, this technology does not become popular till much later on, around the 2010s (Bagher, 2017).

2000s: Acceleration of Touchscreen Displays
In 2007, Steve Jobs introduced the iPhone, and in 2008 the App Store, which popularized smartphones and their touchscreen technology into the mainstream. Many companies had experimented with this technology in 1990s (like Seiko's smartwatch), but it was not of high quality (Evolution of Device Display Technology, 2020). Also during 2007, LCD overtakes Plasma in popularity with its larger and cheaper displays (Walden, 2020).

2010s: Introduction of QLED
Finally in 2013, LG introduces Quantum-Dot Technology (QLED) which is later popularized by Samsung. A revolutionary new technique advancing display technology (Then and Now: The History of Display and LED Technology, 2020).

Q3)

It is evident just by looking at its history, that advancements in displays technologies are being made quickly. A display that may seem extraordinary in its times, is soon taken over my more advanced displays (BBC STORYWORKS, 2020). Nowadays, many argue that OLED (the current, most dominant display on the market) has already reached or is reaching its peak in the near future. The big question that remains is which kind of display technology will take OLEDs place (If OLED has reached its peak, what's the future of TV?, 2020)?

Fortunately, the future of QLED looks promising. Despite OLED's success today, it has major issues with its high price, lower brightness, higher colour loss over time, limited size variability, burn-in and the general slowing rate of advancements as compared with QLED (Garden et al., 2020). The other issues which are not related to its features, are its shorter lifetimes, more expensive manufacturing process, and its lower water and sunlight resistance compared to QLED (Advantages of OLED | disadvantages of OLED, 2020).

The three academic papers discussed cover different aspects of the advantages and disadvantages of QLED over its competitors, primarily OLED. In general, this included:

What exactly makes QLED such a worthwhile investment for display technologies? There are many advantages of QLED including (Advantages of QLED | disadvantages of QLED, 2020):

- longer life due to QLED resisting moisture more (OLED has a shorter lifespan, and less water resistant)
- cheaper due to its high resistance with water, where the expensive process of vacuum evaporation is not required (OLED is more expensive)
- display size ranges are higher, giving customers more freedom (OLED has a limited size range)
- thin in size and light in terms of weight
- turning it on and off is very quick

- brightness is much higher (30% to 40% brighter than OLED display, and 50 to 100 times brighter than CRT and LCD display types)
- lower power consumption which saves energy costs (compared to OLED displays, its twice as power efficient)
- no burn-in (unlike OLED)
- suitable candidate in photomedicine

However, there are some disadvantages, which are constantly being improved including (Advantages of QLED | disadvantages of QLED, 2020):

- light which isn't self generated as backlights are used instead
- bright images can be blurred
- best viewing angles are dead center, otherwise the quality (colour, contrast) decreases
- blue is less saturated
- problems with absolute black

How does QLED work?
Essentially, a layer of quantum dots are placed before a normal LED backlight panel. This layer consists of atomic particles which, according to their size, emit its own unique wavelength of light (hence quantum dots), these differences produce the wide range of colours to the human eye (Hall, 2020).

In conclusion, all three papers agree to varying degrees that QLED has many amazing features many of which are not fully developed yet, but nevertheless the display technology is not going anywhere anytime soon.

More Specifically:

Paper 1: 'Quantum Dot Display Technology and Comparison with OLED Display Technology':
The author Payame Noor, begins with introducing QLED, a new television technology which is made of tiny light-emitting crystals. As of recently, OLED has sent the benchmark for the quality that TVs should aim for (Bagher 2017). OLED beats QLED on deep blacks, contrasts and viewing angles. But QLED supersedes OLED in other areas. It can have better a contrast ratio, power efficiency, colour range, luminance and lower manufacturing costs. Not to mention that QLED has a greater capacity of modification from emerging technologies than OLED (Bagher 2017).

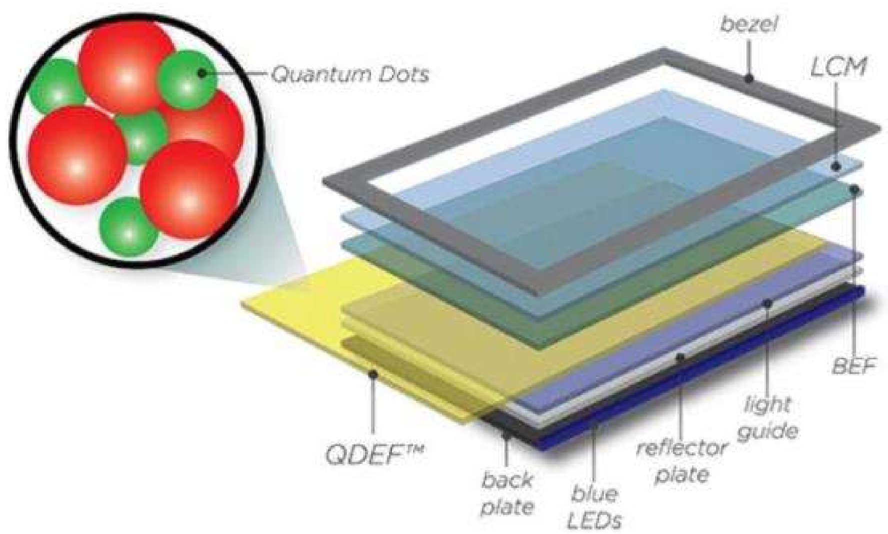

Figure2. *Quantum dot display structure (OLED-TV Displays Infos - OLED-Display.net)*
(Bagher 2017)

Paper 2: 'The Dawn of QLED for the FPD Industry':

In essence the authors, Chaoyu Xiang, Weiran Cao, Yixing Yang, Lei Qian, and Xiaolin Yan discuss how all the rapid improvements with QLED materials and the panel creation processes, QLED has a brighter future ahead compared to its competitors like OLED (Chen 2018). Before QLED can progress, the life time of blue emitters needs to be increased, due to their high energy levels. Another other issue is with the cadmium compounds of which the strongest QLED materials are based from. Lastly, QLED has enormous potential because of its picture sharpness, colour spectrum and high brightness efficiency (Chen 2018).

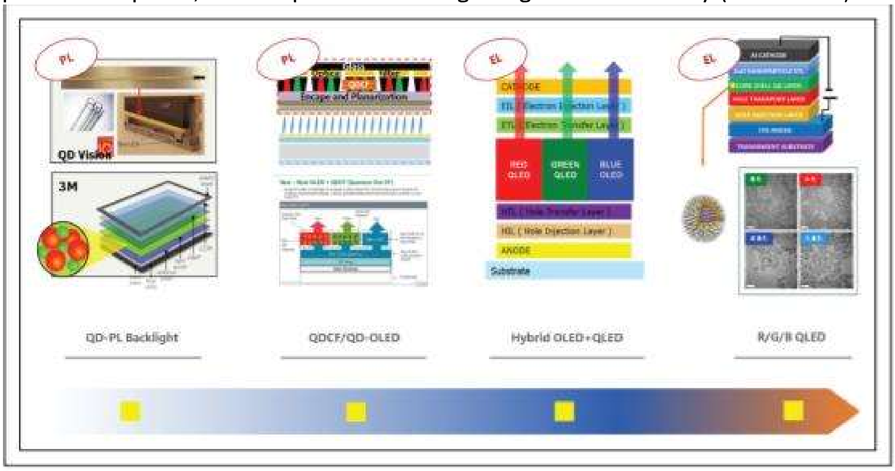

Fig. 1: The evolution of QD technology in flat-panel displays began with QDs for downconversion backlighting and as part of a QDEF film. The next step is a hybrid OLED/QLED display, and the ultimate goal is a fully emissive RGB QLED-based display.

(Xiang 2018)

Paper 3: 'UCF Students Develop QLED Devices for Medical Applications':

The authors Hao Chen and Juan He have been trying to find a cheap but effective lighting device that could be used in conjecture with their clinical applications such as photodynamic therapy (PDT) or photo biomodulation (PBM) (Xiang 2018). They found that QLED fits this criteria well, in particular the pure-color red QLEDs at specific wavelength (around 620 to 670 nm) and high luminance (OLED can not reach this high luminance at specific wavelengths). They found that QLEDS are better than lasers in photomedicine in terms of lower price, larger area covered, and light sources that can be worn (Xiang 2018).

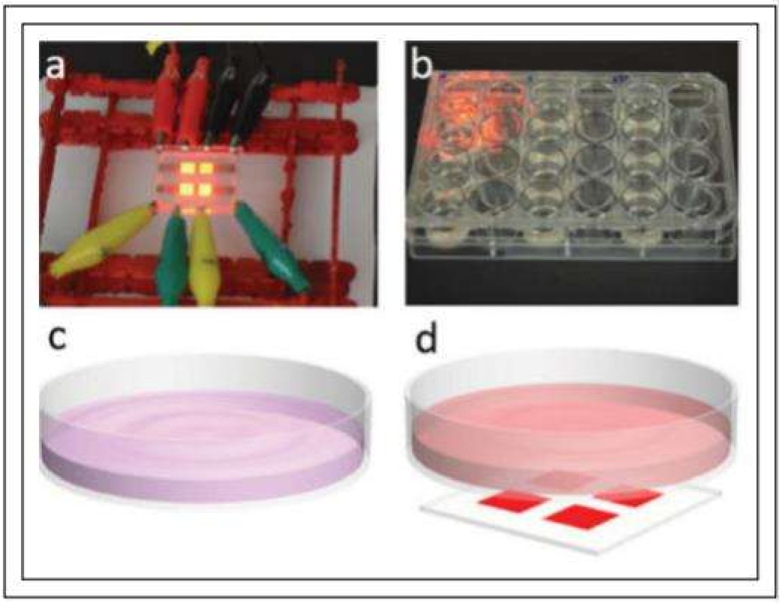

Fig. 2: The experimental setup for photomedical testing included (a) a 2 × 2 red QLED array; (b) an experimental setup; (c) control cell cultures without light treatment; (d) cell cultures using QLED as a light source.

(Chen 2018)

Q4.1) Paraphrasing the 3 Academic Papers

Paper 1: 'Quantum Dot Display Technology and Comparison with OLED Display Technology':

Abstract

LCD has been overtaken by OLED in the last few years, having the highest quality pictures available.
QLED has the potential to match or even be better than OLED display technology in the near future.
Some of these areas include its high contrasts ratios, high power efficiency, and better colours (Bagher 2017).
Note that 'quantum dot display technology' is an alternative term for 'QLED'.

1. Introduction

QLED is made of nanocrystals that emit light. LCD can't emits its own light. QLED mechanisms is similar to LED and LCD systems but more advanced in the way light and colours are emitted, and requires a backlight. OLED is made of organic molecules that produce light that is crisper and brighter than most LCD and LED displays (Bagher 2017).

2. OLED Display

Currently, OLEDs are the primary candidate to replace LCD and LED displays. Some of these reasons being the higher contrasts and wider viewing angles. An important research area is white OLED devices (Bagher 2017).

3. OLED Advantages (Bagher 2017)

1) OLEDs are thinner and lighter than LEDs because of the composition of the organic layers.
2) OLED substrates aren't restricted to glass only, their also more flexible than LEDs.
3) OLEDs are substantially brighter than LEDs.
4) OLEDs don't need to have backlighting unlike LCDs.
5) OLEDs contains plastics and is malleable.
6) OLEDs have bigger viewing fields, approximately 170 degrees.

4. OLED Disadvantages (Bagher 2017)

1) OLEDs on average have a third of the lifespan of LCD.
2) Large OLED displays aren't available.
3) OLED has problems with displaying vibrant colours.
4) OLEDs are easily damaged by water.
5) OLEDs are hard to view with sunlight.
6) The OLED manufacturing process is expensive.

5. Quantum Dot Display

QLED displays are made of tiny inorganic particles a few nanometers wide. The colour emitted by particles depend on their size. QLEDs can exceed the colour accuracy of OLED panels. Its disadvantages are its restricted viewing angles, deep black accuracy and poor contrasts ratios (Bagher 2017).

6. QLED Advantages (Bagher 2017)

1) QLEDs are up to 40% more light efficient than OLEDs at the same colour.
2) QLEDs could be more than twice as efficient with power.
3) Manufacturing costs are lower.
4) Thinner, malleable and transparent QLEDs allow engineers to do more advancements than OLED.

7. Similarities with QLED and OLED Technology

Screen and layer depth capacities are similar. They can also be printed on thin materials as substrates or plastics. Both are highly efficient in terms of energy and made of crystals (Bagher 2017).

8. Differences with QLED and OLED Technology

The crystals in the layers of QLED are inorganic as opposed to organic in OLED. QLEDs are cheaper to manufactures because it's made of inorganic material. OLED has better viewing angles than QLED (Bagher 2017).

9. Result
Although structurally, QLED is similar to OLED there are some clear differences. QLED displays have lower manufacturing costs and higher energy efficiency. When OLED entered the market, it completely overtook its competitors, however QLED is now a better option for displays than OLED. It can alse produce brighter lights and a wider colour range (Bagher 2017).

<u>Paper 2: 'The Dawn of QLED for the FPD Industry':</u>

Abstract
QLED display technology will be easier to commercialise if their lifetimes are extended, and investments are made to manufacture inkjet printing (Xiang 2018). Note that QD refers to QLED and 'luminescence' refers to the brightness of QLED nanoparticles (Xiang 2018).

Introduction
QLEDs are a perfect light emitting particles for flat-panel displays(FPDs). The sizes and shapes of these particles can be controlled easily and offer a wide range of colours (Xiang 2018).

Development of QD Applications in FPDs
QLEDs have issues in emitting blue light. However, some benefits include that's QLED is ideal for large-area printing. The inorganic materials that make up QLEDs are robust and more resistant than the organic materials in OLED (Xiang 2018).

Improving Efficiency
Higher brightness can be achieved if its properly balanced with electric charge conduction.Thus, new engineering to redesign the QLED structure is required (Xiang 2018).

Lifetime Issues
To have the best chance of high commercilisation, the lifetime of QLEDs needs to be improved. To do so, conduction of electric charges needs to be balanced with QLEDs's luminescence. Luminesence and electric charge are closely related in physics due the role of electron in an atom (Xiang 2018).

Solution Processing
QLED has issued with being manufactured in large sizes during mass production. Inkjet printed QLED devices have lower lifetimes and efficiency (Xiang 2018).

Outlook
Due to rapid developments in QLED display technology, QLED has a bright future ahead. Some of the issues that need to be solved, before QLED achieves any major success include emission of blue light, and how it lowers the lifetime. Then with Cd compounds, the material that produces the highest QLED performance, needs to be cautioned due to its detrimental environmental impacts, and their colour purity are also troublesome. Also, with producing higher resolution panels, the inkjet printing method during manufacturing needs to be improved. In conclusion, due to its excellent potential QLED is likely to be the next trend in display technologies (Xiang 2018).

<u>Paper 3: 'UCF Students Develop QLED Devices for Medical Applications':</u>

Abstract
The authors Hao Chen and Juan He have been trying to find a cheap but effective lighting device that could be used in conjecture with their clinical applications such as photodynamic therapy (PDT) or photo biomodulation (PBM) and improve their issues (Chen 2018).

Introduction
Photomedicine is a new field of medicine that aims to kill cancer cell via use of light from devices such as QLED. Unfortunately, the light from lasers and LEDs have not been effective. OLEDs aren't favoured because they can not reach the required high luminance. Thus QLEDs have been a prime candidate, especially in the red spectrum (Chen 2018).

Finding a Suitable Problem
The results of the study involving the red light spectrum of QLEDs looked promising (Chen 2018).

Preliminary PBM Results
A 4 pixel QLED array was used as a photomedical light source for the study. The results showed that QLED PBM increased the metabolism of some cells. This proves to be promising (Chen 2018).

Preliminary PBT Results
A frequently used human line cell type was used to interact with the red QLED light. The results showed that low dose PDT where QLED acted as the light source proved to be effective low cost (Chen 2018).

Wavelength Tunable Red QLED for Targeted Photomedicine
The promising results for the PBM and PBT tests were used by really bright QLED light that had a wavelength of about 620 nm. However, more control over these wavelengths are needed to see better results. Currently, the most controlled wavelength is conducted out by expensive and large equipment (Chen 2018).

Facing Challenges, Lessons Learned
More understanding was required of improving QLED performance. Cadmium in QLED materials can also be dangerous to body with side effects. Teamwork was a big skilled worked on (Chen 2018).

Working Toward a Flexible Implementation
To build upon the work of this experiment, flexible QLED devices are required to be used on plastic substrates. Stability is a key feature needed to be improved. The results of the PBM and PDT experiments, should be inspire others to investigate the effects of bright red QLEDS to improve phototherapy applications. If the commercialisation of QLEDs are more successful, then its medical application can be enhanced (Chen 2018).

Q4.2) 2 Common Main Aspects between the 3 papers

Main Aspect 1: QLED emits a higher range of light intensity and colour, than its competitors inc OLED.
Another common concept shared between the papers, was the more useful quality of light being emitted by QLED displays. This is in terms of the higher range of brightness and colour.

In physics, light can be thought of as a wave and particle. If a light source is emitting a higher light intensity (brightness), it means that more photons are being emitted. If a light source, changes the colour of the light being emitted, the wavelength of its photons are changed. A photon is emitted from an atom, when an electron changes energy levels.

In Paper 1, Noor discusses how QLEDs are up to 40% more light efficient than OLEDs at the same colour (Bagher 2017). Similarly in Paper 2, the authors discuss that even higher brightness can be achieved if its properly balanced with electric charge conduction (Xiang 2018). Comparably in Paper 3, Chen and He examine that OLEDs aren't favourable because they can't reach the required high luminance required for photomedicine procedures like PBM and PBT, but QLED can (Chen 2018).

In regards to the higher colour range of QLEDs, in Paper 1, Noor discusses how the colour emitted by the nanoparticles depend on their size, and that QLEDs can exceed the colour accuracy of OLED panels (Bagher 2017). Similarly in Paper 2, the authors examine how the sizes and shapes of these particles can be controlled easily and thus offer a wide range of colours (Xiang 2018). Comparably in Paper 3, Chen and He discuss how only the specific wavelengths of lights in ultrabright red spectrum are suitable for photomedicine especially since they can be easily controlled (Chen 2018).

Main Aspect 2: QLED is made of Inorganic Material, which has pros and cons, OLED is organic.
A common concept discussed between all three papers was the advantages and disadvantages of using inorganic material, most notably the compound Cadmium, in QLED displays. Cadmium is often chosen as it's the strongest inorganic material available (Xiang 2018).

In Paper 1, 'Quantum Dot Display Technology and Comparison with OLED Display Technology', Noor highlights that the crystals in the layers of QLED are inorganic as opposed to organic in OLED. As QLEDs are made of inorganic material they reduce costs in the manufacturing process, and are overall cheaper than OLED (Bagher 2017). Similarly in Paper 2, 'The Dawn of QLED for the FPD Industry', the authors discuss how the inorganic materials that make up QLEDs are robust and more resistant (to sunlight and water) than the organic materials in OLED (Xiang 2018). Contrastingly in Paper 3, 'UCF Students Develop QLED Devices for Medical Applications', Chen and He discuss how Cadmium in QLED materials can be dangerous to body with side effects and be detrimental to the environment (Chen 2018).

Q4.3) Comparing there 2 Aspects, with normal standards in Display Technology (OLED sets the benchmark)
As mentioned previously, OLED has set the benchmark for all display technology tests today.
The two major aspects discussed in the earlier section was the type of material in the display type, and the light quality emitted by the display technology's nanoparticles (Kanter 2020).

OLED uses organic material, where as QLED uses inorganic material namely Cadmium (Xiang 2018). This makes QLED more robust and more resistant to the damaging effects of direct sunlight and water. Not to mention it has a longer lifespan partly due to these factors. Lastly, the use of inorganic material makes the manufacturing process a lot cheaper, and hence for the customer, QLED is a more affordable option (Xiang 2018).

QLED can reach a higher brightness and colour range/vibrancy than OLED. QLED can have up to 40% more brightness than OLED, and can easily control the wavelength of light emitted by its nanoparticles allowing for a larger spectrum of richer colours (Bagher 2017). On the other hand, for image quality, OLED has better deep blacks, sharpness, contrast ratios and saturation (especially blue light) (Chen 2018).

Q4.4) Conclusion: Pros/Cons of, QLED, OLED, which will win in the end?

In short, the benefits of QLED over OLED are (Bagher 2017):
The longer life due to QLED resisting moisture more (OLED has a shorter lifespan, and less water resistant). Cheaper price, due to its high resistance with water, where the expensive process of vacuum evaporation is not required (OLED is more expensive). Display size ranges are higher, giving customers more freedom (OLED has a limited size range). Thin in size and light in terms of weight. Turning it on and off is very quick. Brightness is much higher (30% to 40% brighter than OLED display, and 50 to 100 times brighter than CRT and LCD display types). Lower power consumption which saves energy costs (compared to OLED displays, its twice as power efficient). QLED faces no burn-in (unlike OLED). Lastly, it is a suitable candidate in photomedicine.

However, there are some disadvantages to OLED, which are constantly being improved including (Bagher 2017):
The light which isn't self generated as backlights are used instead. It's bright images can be blurred and the best viewing angles are dead center, otherwise the quality (colour, contrast) decreases. Also with colour, its blue is less saturated. There are minor problems with absolute black.

In conclusion, it is fair to deduce that given that the sheer potential and current advantages that QLED has over OLED, it far outweighs its disadvantages. Even though it might take some years for the display technology to advance substantially, ultimately QLED will win out in the end.

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