White Light Emitting Diode as Liquid Crystal Display Backlight

By

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ABSTRACT

The discovery of high brightness (white) light emitting diode (LED) is considered as a real threat to the current lighting industry in various applications. One of the most promising sectors would be using white LED to replace the current Cold Cathode Fluorescent Light (CCFL) technology as the backlight of the large screen Liquid Crystal Display (LCD) screen due to the fact that LCD is a rapidly booming market.

Thesis advisor: Professor Thomas W. Eagar
Title: Thomas Lord Professor of Materials Eng & Eng Sys

Acknowledgements

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Chapter 1
Introduction

The discovery of AlGaInP based and InGaN based semiconductors have revolutionized the usage of light emitting diode (LED) from being as small indicator light into wide range of applications like LCD backlighting and general lighting. LEDs are getting most of the attention for lighting technology mainly due to the long life span and the energy efficiency.

1.1 Brief history of Light Emitting Diode (LED)

In 1907, H.J. Round discovered that when he applied a large voltage (>100V) to a SiC crystal, light was generated from the transformation of electrons into photons which was named as electroluminescence.

In the 1960s, electroluminescence was studied extensively on III – V semiconductor alloys such as GaAs or GaAsP. In 1962, the first visible red emitting LEDs were made of GaAsP. In 1968, the first commercial red GaAsP LEDs were introduced to the marketplace by Hewlett Packard. However, defect density has great influence on the performance of such LEDs, the higher the defect density the lower the light emitting efficiency.

In the 1970s, AlGaAs/GaAs single heterojunction diodes were proposed and developed. By increasing the Al-fraction, AlGaAs/GaAs emission wavelength can be reduced until 660 nm (red). AlGaAs bandstructure becomes indirect at high Al-fractions, therefore it was not possible to fabricate AlGaAs LEDs emitting at wavelengths shorter than 660 nm. The next advancement was the introduction of double heterostructures which has better confinement of electrical carriers in the active region of the device.

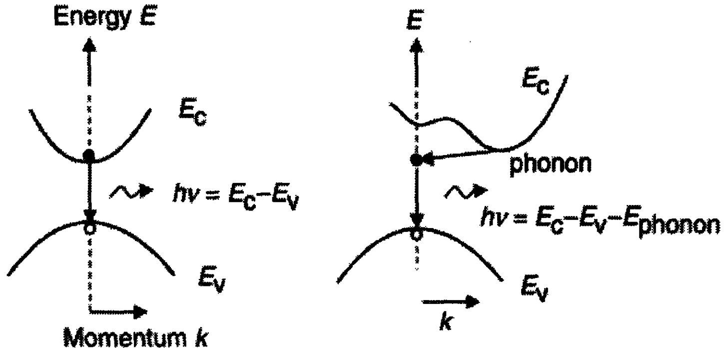
Subsequently, to get emission wavelength less than 660nm, AlGaInP system was investigated intensively. The quaternary composition of AlGaInP allowed the bandgap to be tuned from yellow green to red while maintaining the same lattice constant.

To further reduce the emission wavelength, the material system of GaN was investigated. In 1989, a Japanese group solved the problem of p-doping in GaN real by activating Mg dopants with low-energy electron-beam irradiation. Nichia Chemicals brought the first commercial blue GaN-based LEDs to the market in 1994. By adding Indium to form the InGaN alloy, Nichia fabricated the first blue-green (500 nm) and green (520 nm) LED. Therefore, we have entered the solid state lighting era.

1.2 Principles of Light Emitting Diode (LED)

LED is a semiconductor device that emits nearly monochromatic light under the forward bias. LED consists of n- and p- type semiconductors putting together to form a p-n junction where electrons and holes are injected into it. LED generates light via the excitation of an electron into higher energy state and the relaxation of the excited electron back to the lower energy state after it meets a hole. The conversion of electrons into photons is called electroluminescence. The emission wavelength can be tailored from infrared to ultraviolet by using different semiconductor materials.

The band structure of the semiconductor material can be either the direct band structure or the indirect band structure. In the direct band structure, the relaxation of the excited electrons from the conduction band into the valence band can occur under momentum conservation. While for the indirect band structure, the relaxation process needs the assistance of phonon to achieve momentum conservation. Hence the indirect band relaxation is less probable.



(a) (b)

Figure 1.1 (a) Direct bandgap band-band transition (b) Indirect bandgap band-band transition [1]

The relaxation of the excited electrons from the conduction band into the valence band is characterized by the recombination rate of electrons with holes. The recombination rate is proportional to the density of electrons, the density of holes, and a proportionality factor which is a measure of the probability of the recombination.

Other than the band to band transition, there are several other mechanisms like: 1) band to impurity level transition, 2) donor states to acceptor states transition, and 3) Auger recombination process. The first two transitions are similar to the band to band transition but the Auger recombination process is undesirable. For Auger recombination, the energy released during electron hole pair recombination may be transferred to other carriers and then be dissipated as phonons instead of generating photons.

The center emission wavelength of an LED can be obtained by the bandgap energy $\lambda = hc/E_g$. By using high doping levels or graded substrates, the linewidth of the emission spectrum can be increased. For all LEDs that use band to band transition, the emission spectrum measured at the top side differs from the emission spectrum measured at the side.

The efficiency of light generation inside an LED is very high (>90%), however the extraction efficiency of light from the semiconductor material is only a few percent. This is because semiconductors' refractive index is in the range of 3 to 3.5 while the surrounding medium is having refractive index in the range of 1 to 1.5. As a result, the interface of semiconductor and the surrounding becomes a good reflection plane to prevent the light coming out from the semiconductor material. Nowadays, individually shaped dies are being employed to solve this light extraction problem for high brightness LED.

1.3 White LED

The discovery of wide bandgap InGaN-based semiconductors has enabled the LED to emit white light. The group III nitrides allow the generation of ultraviolet (UV), blue, green and white light. Theoretically, the InGaN-based semiconductors can cover a wide wavelength range up to 630nm.

Currently, color temperature and color rendering index (CRI) are being used to measure the quality of white light. Color temperature is based on black body radiation spectrum and the common standard for white light is the Illuminant C which describes sunlight with color temperature around 6770K[1]. CRI describes the light source with reference to sunlight in the scale of 0 to 100. Usually CRI of eight samples being illuminated by the light source will be tabulated with reference to sunlight, subsequently the final CRI of the light source will be obtained from the arithmetic average [2].

The most common way to achieve white LED light is by adding an inorganic phosphor like yttrium aluminum garnet (YAG) doped with rare earth elements cerium (Ce) into a blue LED. By adjusting the amount of phosphor powder in the LED die, different color temperature and color rendering index can be achieved. Therefore, it is important to have consistent phosphor deposition during the packaging process in order to have consistent white LED product. Nevertheless the emission light appears to be bluish or cold white due to the low level of absorption in the phosphor.

Another common method is to use Red + Green + Blue (RGB) LEDs in order to produce white light but this multiple chips approach has the disadvantage of large unit area and multiple connections. Each LED must be controlled properly by separate circuits in order to have proper white light generation.

In order to generate high-performance white light, white LED can also be made by incorporating a two- or three-color phosphor into a near UV LED. For an instance, this is done by coating the near UV LED with red and blue phosphor plus aluminium doped zinc sulfide and green emitting copper. Currently, Yuji Uchida and Tsunemasa Taguchi have developed orange (O), yellow (Y), green (G), and blue (B) white LEDs consisting of OYGB phosphor materials and a near UV LED [3]. This OYGB LED is much superior than the two most common methods as shown in the table below.

White LED uses no phosphors at all is being researched too. It is based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate and quantum dot white LED. [4]

	Blue-YAG	RGB	OYGB
Luminous efficacy	>50 (lm/W)	>30 (lm/W)	>40 (lm/W)
Typical color temperature (Tc)	6500 K (day light)	4000 K (day light)	3700 K (white)
General color rendering index (Ra)	>80	90	>93

Table 1.1 Comparison of OYGB LED with the two most common white LEDs [3]

Nevertheless, another important factor luminous efficacy (SI units of lumens/watt) which characterizes white LED should not be ignored too. Luminous efficacy measures the fraction of electromagnetic power which falls in visible spectrum by dividing the luminous flux over the radiant flux. For an instance, the requirement for large format LCD backlighting is around 60-70 lumens/watt. Therefore, in order for white LED to replace the existing lighting technology, great improvement of luminous efficacy is needed.

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[1] Visible light-emitting diodes by Klaus Streubel

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Chapter 2

Trends in Liquid Crystal Display (LCD) Backlighting

The types of LCD backlighting will be introduced in this chapter. The role of white LED as a potential disruptive technology in large format LCD (especially LCD TV) backlighting is also discussed. The role of LCD brightness enhancement films will be briefly discussed to examine its role for white LED backlighting.

2.1 Current competing technologies

2.1.1 Cold cathode fluorescent lamps (CCFL)

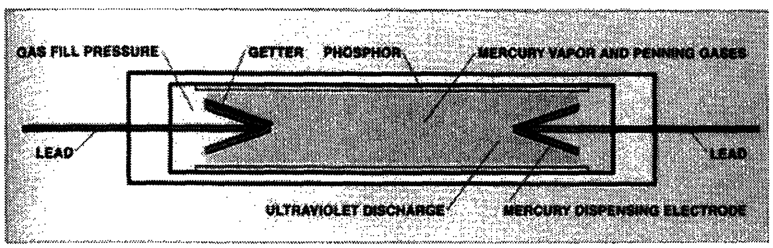

Figure 2.1 Typical structure of CCFL for backlighting [1]

Currently CCFL is the main backlight for the LCD outside of mobile applications. CCFL consists of a phosphor coated glass tube with rare gases and mercury inside. It is "cold" because there is no filament inside the glass tube to intentionally heat up the gas. A high bias is applied across the two electrodes and ionizes the gas in between. Some of the electrons created from the gas ionization will hit the electrodes. As a result more and more electrons are emitted from the electrodes which in turn excites the coated phosphorous which emit visible light with the help of the mercury. Brightness enhancement films are used together with CCFLs in LCD backlighting.

2.1.2 External electrode fluorescent lamps (EEFL)

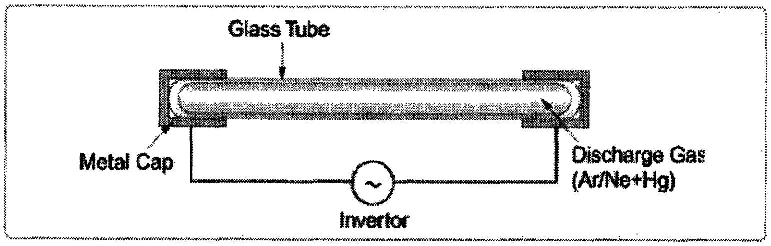

Figure 2.2 Typical structure of EEFL for backlighting [2]

As the name implies, EEFL has external electrodes and allows just a single inverter to drive all the lamps as compared to CCFLs which require multiple inverters. Developers of EEFLs claim a longer lifetime and higher power efficiency than CCFLs. The longer lifetime is mainly due to the fact there are no electrodes in the lamps and hence no electrode burn out issue. Using just one inverter to drive all the EEFLs in parallel enables uniform brightness, lower power consumption and lower heat generation. Besides, reducing the number of inverters allows a more compact LCD design. Currently, LG Philips LCD is promoting this technology. The usage of brightness enhancement films for EEFL is similar to CCFL.

2.1.3 Flat Fluorescent Lamps (FFL)

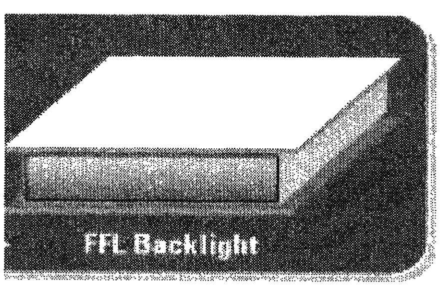

Figure 2.3 Typical structure of FFL for backlighting [3]

The FFL is a single large area lamp as compared to the multiple CCFL or EEFL lamps. The advantages of FFL are: mercury free, wider color range than the traditional CCFL, higher contrast and image quality, possibly elimination of the need for brightness enhancement films which are needed by CCFL and EEFL, improvement in mechanical assembly since it uses only one lamp and lesser inverters. Nevertheless, it is challenging to manufacture a single FFL tube uniformly in large areas which means the manufacturing cost presently is high. Therefore, it is questionable whether the manufacturing cost of FFL can be reduced significantly given that the LCD TV size is becoming larger and larger. Currently, this approach is championed by Samsung Corning.

2.1.4 Hot Cathode Fluorescent Lamps (HFCL)

As the name implies, HCFLs have heated electrodes and hence are able to emit higher currents since thermionic electron emission is more efficient than the secondary electron emission of CCFL (50mA to 1A as compare to only 10-20mA for CCFL). As a result, HCFLs require larger diameter tubes (typical 16mm as compare to 2-4mm for CCFLs) to accommodate the higher current. The larger diameter tubes of HFCL give rise to higher light output than CCFL and hence can be operated in scanning mode. The scanning mode improves the LCD picture quality significantly with respect to both motion blur and contrast in dark scenes. Besides, HCFLs do not require lesser brightness enhancement films due to the high light output.

2.2 White LED as the disruptive technology?

Currently, there is an interest regarding White LED as a disruptive technology in large format LCD backlighting. There are some exaggerations therefore this section is going to examine the real strengths and weaknesses of White LED as the backlighting of large format LCD.

The Advantages of White LED are:

- Brightness and Uniformity
- Dynamic Contrast Control
- Long life - No Bulb Replacement
- High Color range - Dynamic Color
- Less Noise, Reduce motion blur
- Instant On/Off
- Rugged, Environmentally Friendly - No Mercury
- Low voltage
- Low Pressure - Safe Operation, No Explosion

White LED backlighting is already a dominant force in mobile LCD backlighting; currently it takes up about 85% of the mobile LCD and other small screen LCD backlighting market due to the fact it does not require bulky inverters at all. Therefore, white LED backlighting LCD has the advantage of slim profile which can be translated into a big selling point for large format LCD consumer products like laptops and LCD TVs. An array of White LEDs injecting light into a notebook computer screen from the bottom is now the standard approach for creating ultra-thin notebooks.

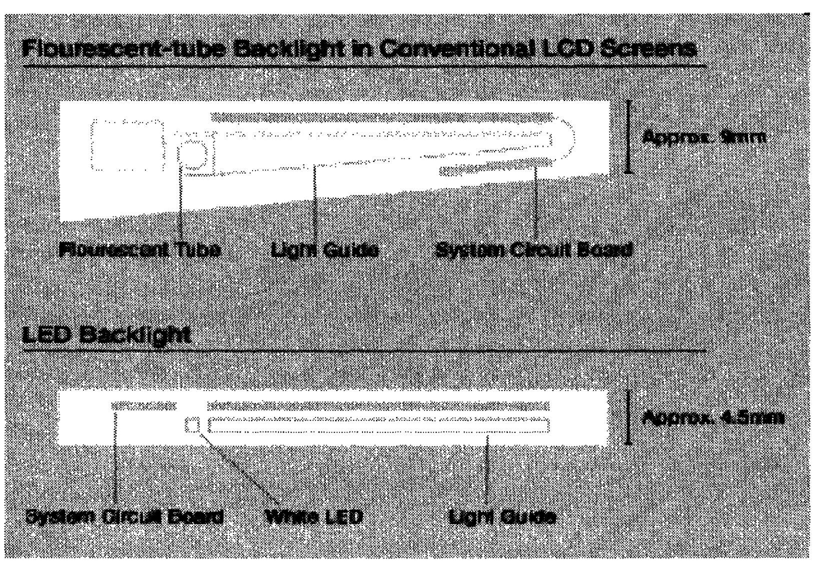

Figure 2.4 The slim profile of LED backlight [4]

As the performance of white LEDs becomes better and better in lumens/watt (which will be discussed in the following section), more and more large screen LCD producers are looking into the possibility of using white LED backlighting.

	CCFL	EEFL	LED	OLED	FFL
Price (Now)	1X	1X	2.5X~3X	?	?
Price (2H'06~1H'07)	1X	0.9X	1.8X~2X	?	?
Strike Voltage	1KV~1.2KV	1.5KV~2.5KV	<10V	<10V	24V
Color Gamut (NTSC)	70%-72%	70%-72%	100%	100%	80%
Life Time (Hours)	50K~60K	>60K	50K	12K~15K	100K
Gas	Ar. Ne	Ar. Ne	-	-	Xe
Power Consumption	Fair	Good	Excellent	Good	Not Good
Inverter Design/Cost	Easy/Low	Lower	Easy/Low	Easy/Low	Very Easy/Very Low
Lamps # (32")	16	20	-	-	-
Mecury	4mg	<4mg	Free	Free	Free
Color Uniformity	OK	OK	Not Good	OK	?
Brightness Efficiency(Lm/	60~80	60~80	20~30	20	30
Supply Status	Open	Limited	Complex	?	?
Issues to be solved	Mecury Supply Issue Color Gamut	Supply issue 40"+ Large Size	Cost Thermal Control Circit Complexity Design Structure	Lifetime Productivity Design Structure	Productivity Power Consumption Cost

Figure 2.5 Comparison of White LED with other backlighting technologies [4]

The diagram above shows the comparison of White LEDs with other backlighting technologies where OLED stands for Organic Light Emitting Diode and FFL stands for Flat Fluorescent Light. It can be seen that White LEDs have the advantages in functionality among existing and emerging large format LCD backlighting technologies. Besides, White LEDs have the advantage of being mercury free and consuming very little power; hence White LED has the advantage of being a green technology which is the major trend going into the future.

Nowadays, cost reduction is a major concern in large format LCD displays because of the severe price war in the display industry. As a result, this results in slow adoption rates of White LED as large format LCD backlighting. Nevertheless, the slim profile, better color rendering index, power efficiency, and being a green technology of White LED may offset the cost disadvantage in the long run. In addition, large-screen (> 40 inch) models are big-ticket items costing several thousand dollars, so adding White LED backlights that may cost an extra few hundred dollars should be acceptable in this particular premium market. Furthermore, with brightness increasing, the same illumination can be achieved with fewer White LEDs as time passes, thus resulting in reducing costs.

Therefore, the challenges to be solved for rapid penetration of White LEDs as the backlighting of large format LCD are: cost, heat dissipation, color uniformity, efficiency (Lumens/watt) and control circuit complexity of the White LED chip. The Orange Yellow Green Blue White LED which is discussed in the next section is poised to solve the color uniformity, efficiency and perhaps the cost problems.

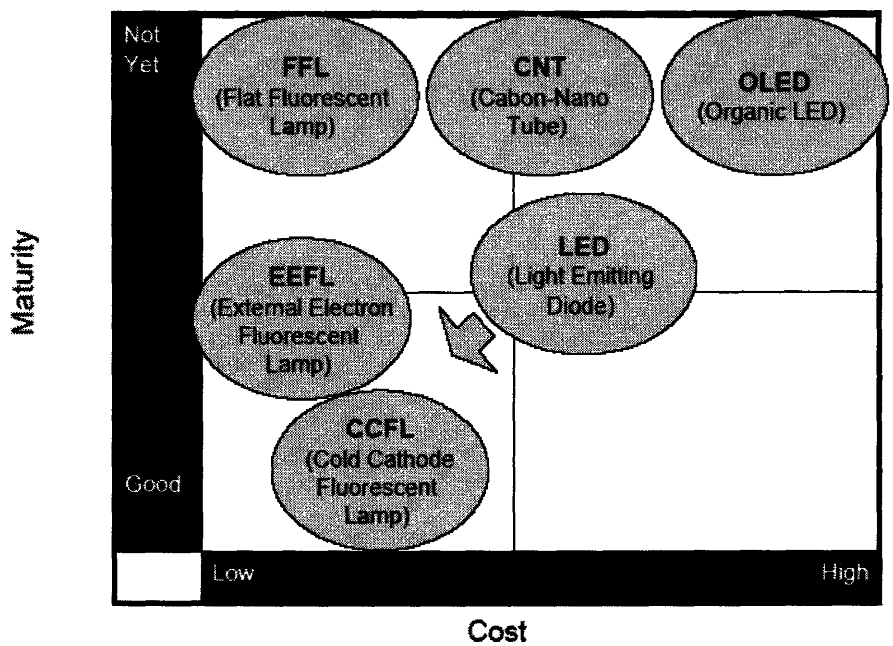

Figure 2.6 The current positioning of White LED as large format LCD backlighting [4]

2.3 Different approaches of White LED backlighting

Currently there are two major approaches in using White LED as backlighting of large format LCDs. These include YAG coated blue LEDs or Red+Green+Blue (RGB) LED to generate the white light.

2.3.1 YAG coated blue LED

The YAG coated blue LED uses a white LED emitter to feed light into a backlight from the edge. While this approach has a lower color range than CCFL (and some color inconsistency of white from LED to LED), it offers excellent compactness and good efficiency. An array of white LEDs directly behind the LCD panel for LCD TVs has also been developed. It suffers from color range issues as well as variation in the white light from LED to LED.

In the YAG coated blue LED, the blue light is the major component of YAG generated white light, which is strongly affected by temperature and drive current. The generated bluish white appears to be slightly different from the natural white light and hence does not have a good color rendering index.

2.3.2 RGB LED

Another approach for LED illumination is to use an array of red, green and blue LEDs and mix their light to create white light. This has the advantage of a superior color range and is being introduced for LCD TV applications whereas the above mentioned YAG coated blue LEDs are mainly used for laptop backlighting.

This approach requires more LEDs since four LEDs are used to replace one white LED (2 green, 1 red and 1 blue). Therefore inevitably the costs associate with this approach is even higher than the YAG coated blue LED approach. The edge and direct backlighting methods mentioned above apply here too. Similarly, this RGB approach suffers from variation in the white light from LED to LED.

The RGB approach has a broader spectrum than the YAG coated blue LED since it consists of Red, Green and Blue light It is not strongly affected by temperature and drive current. RGB generated white light is much closer to the natural white light which consists of seven colors and hence has a better color rendering index.

2.3.3 Orange Yellow Green Blue (OYGB) approach

	Blue-YAG	RGB	OYGB
Luminous efficacy	>50 (lm/W)	>30 (lm/W)	>40 (lm/W)
Typical color temperature (Tc)	6500 K (day light)	4000 K (day light)	3700 K (white)
General color rendering index (Ra)	>80	90	>93

Figure 2.7 Comparison of three white LEDs on luminous efficacy, color temperature, and color rendering index [5]

As the name implies, this approach uses an array of orange, yellow, green and blue LEDs and mixes their light to create white light. As a result, it can be seen from the diagram above that the OYGB approach will have a much better color rendering index which means the white light is very close to the natural white light. The OYGB approach is basically an enhanced version of the RGB approach.

Sandia National Lab is currently researching ScGaN and YGaN in order to generate orange and yellow color LEDs without using phosphorus via bandgap engineering. The data of OYGB shown in the diagram above are based on the phosphor coated near-UV LED to generate the orange and yellow color. Therefore, by eliminating the requirement of phosphorus, the luminous efficacy of OYGB approach can be greatly improved since there is no loss of conversion efficiency due to the phosphor.
Consequently, color uniformity and luminous efficiency issues can be solved by this promising phosphorus free OYGB approach. However, this approach requires more LEDs and hence the costs may be higher. Nevertheless, there will be cost reduction in getting rid of phosphor.

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[5] Yuji Uchida et al, Lighting theory and luminous characteristics of white light-emitting diodes, Optical Engineering 44(12), 124003 (December 2005)

Chapter 3

Trends in LCDs

This chapter discusses about the trends in LCDs (focus in TV market) since the future of White LED backlighting is related closely to the trends. The market of flat panel displays is experiencing rapid growth with the advancement of digital technologies in media, broadcast and communication. For example, LCD panels have created a new lifestyle for consumers with their thin profile, light weight, and improvements in image quality, size and resolution.

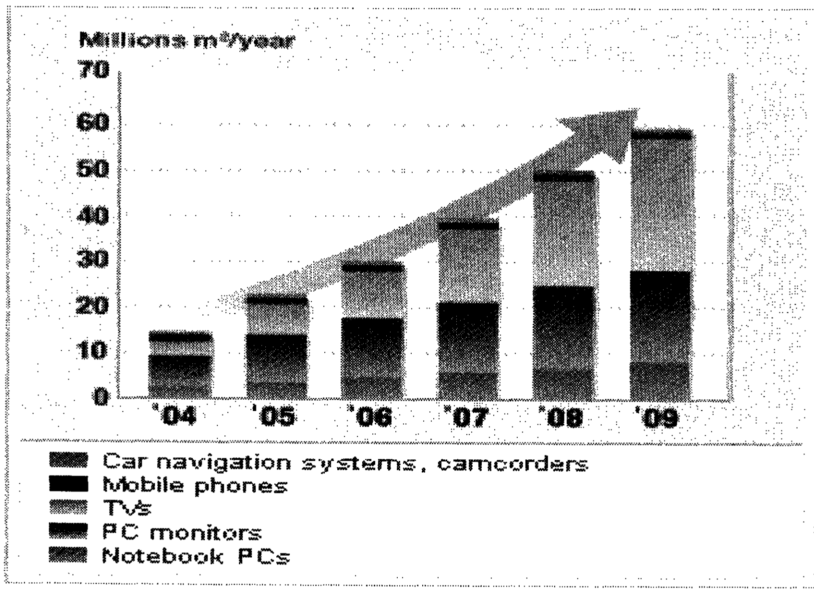

Figure 3.1 LCD market's break down via each application's area [1]

LCD displays are gaining market share in the display marketplace by improving the performance and lowering the cost constantly. Currently, LCDs are taking share rapidly in the TV market. For instance, in 2005 LCD TV manufacturers dominated the 32" TV market while in 2006 sales of LCD TVs in the size range of 37-42" are increasing rapidly.

LCD manufacturers are building more and larger fabs in order to produce larger LCD TV sizes which are believed to be the future trend of TV. Price reduction enables large share gain, and provides the volumes to increase manufacturing productivity while reducing costs.

LCD plants reached eighth generation now (size of 2.16x2.4 meters); each generation almost doubles the size of previous generation. The larger the size, the manufacturers will be able to lower the cost per unit area more. In addition, the throughput and yield are improving with the increasing of size too. Sharp is planning to build a tenth generation fab in the third quarter of 2007 which can produce LCD of size 2.85x3.05 meters (can be used to manufacture 57 inches to 65 inches panels).

In order to keep up with the increasing production capacity of new LCD fabs, the manufacturers believe that LCD TV market is the solution. This is because TV is considered as a necessity nowadays and large size, flat and high definition TV (greater than 30 inches) is deemed to be the future trend. Besides, the latest generation fabs are only efficient in producing the designated larger size LCD panels. For example, the eighth generation fabs are optimized for 46 to 47 inches LCD panels but not for smaller panels with smaller pixels requirement.

In the current greater than 40 inches diagonal TV market, LCD TVs face tough competition from existing technologies like Plasma TVs, rear projection CRT TVs, and microdisplay-based rear-projection TVs. LCD TVs enter the market as a challenger in the 30-36 inches segment facing CRT TVs and are winning convincingly. In the 36-46 inches segment facing Plasma TVs and microdisplay-based rear-projection TVs. In the 46-56 inches segment facing Plasma TVs, rear-projection CRT TVs and microdisplay-based rear-projection TVs. Plasma TVs, which used to dominate 36-46" sizes, are moving upscale to the 46-56" segment because of the cost reduction race from LCD TVs.

Plasma TVs dominates the 40 inches diagonal TVs and larger. Plasma display makers have been aggressively reducing costs and pricing, with prices down 40% or more from 2004 to 2005. Therefore, in order to grab more market share LCD TVs must match or exceed the price reductions for plasma displays. The good news is LCD costs rise slower than plasma as the size increases. Furthermore, LCD TVs have more suppliers and the internal manufacturers devoted more resources into the market.

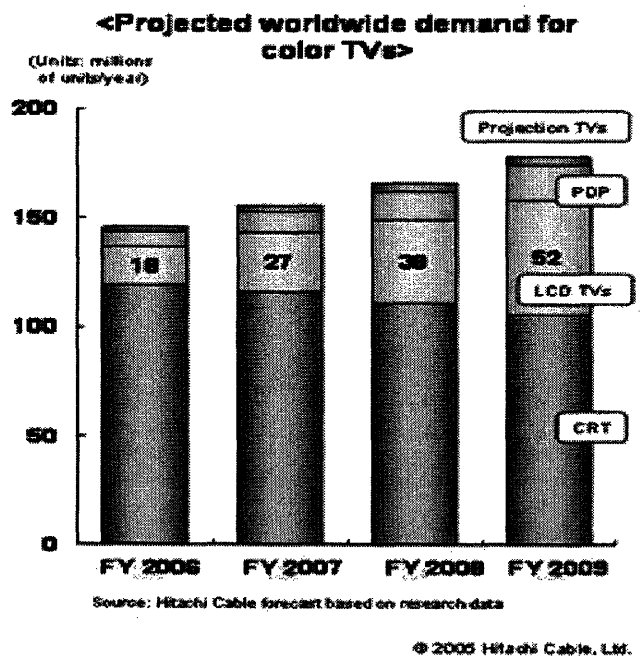

Figure 3.2 Projected worldwide demand for color TVs [2]

At the end of 2005, designers began using White LEDs and flat fluorescent lamps (FFLs) in backlights, instead of the conventional cold-cathode fluorescent lamps (CCFLs). In the near future, non-CCFL backlights are likely to become the mainstream for LCD TVs measuring 50 inches and larger in order to have more superior features like better viewing angle and wider color range. As a result, LCD TVs will be able to compete competitively with the rest.

In fact, LCD TVs offer superior or equivalent features to all other competing technologies except for viewing angle. The major problem of LCD TVs is its higher cost per unit area than all other competing technologies due to the capital costs and material costs. This is the main reason for the slow adoption rate of the more expensive White LEDs backlight. Nevertheless, efforts are being made in reducing the material costs and ramping up the production volumes to achieve lower cost per unit area. Performances versus cost issues of White LEDs backlight will be discussed in the subsequent chapter 4.

The use of LCD TVs as primary (big-screen) household televisions is expected to grow because of the current trends like the move to digital broadcasting format, the emergence of high definition disc like Sony's Blue Ray disc, and the incorporation of networks into the home theater system to enjoy digital videos and music. Significant progresses are being made in LCD TVs features such as thin profile, light weight, low power consumption, high contrast in brightly lit viewing environments, as well as resolving display response with moving images, and brightness where White LED backlighting plays a significant role.

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Chapter 4

Performances versus Cost of White LEDs

Cost is the biggest obstacle for the adoption of White LED especially in large format LCD's backlighting.

4.1 Overview

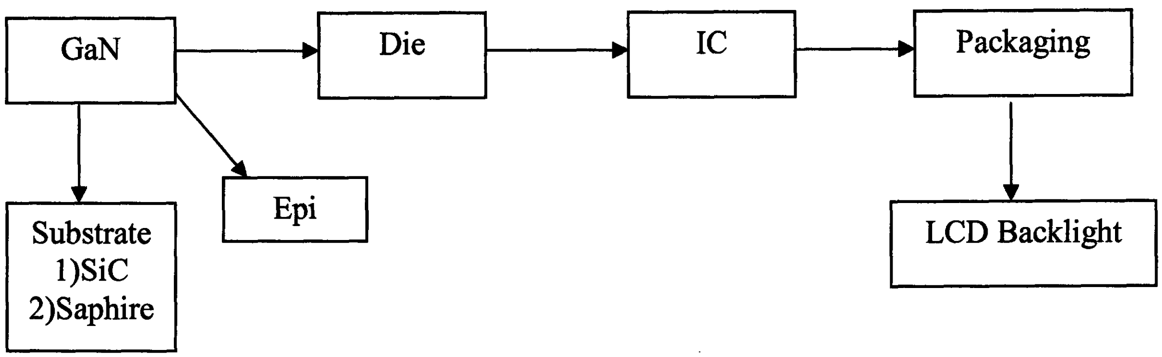

Figure 4.1 Process flow

White LED backlights are basically standard in cell phones now, and they are starting to gain some ground in TVs and laptops. The overview of LCD TVs has been discussed in chapter 3. Currently LED backlights are already starting to become a major technology in laptops. For an instance, Apple has decided to adopt LED backlights for all laptops from 2008 onwards. In the US$2,000+ segment of "executive" laptops of major laptop manufacturers (Sony, Toshiba, etc) is beginning to show several models with White LED backlights too.

The important thing to note here is that the introduction is still more or less limited to high-end laptop displays. The major problem is that the selling price of the display is very close to the production cost, so it is hard for display manufacturers to adopt the higher price White LED (2-3 times more expensive than CCFL). The exception is for high-end laptops because White LED backlights enable a much thinner profile. Battery life is also better because White LEDs consume much less power than CCFL, but the types of laptops in which these are appearing are of the ultra-slim variety, as a result the mentioned advantage is offset by the smaller and lighter battery.

White LEDs are sold per unit in large volumes. However, there is more that goes into the LED than simply the cost of silicon. First, there are the operating costs of the facility and the equipment that make the White LEDs like Metal Organic Chemical Vapor Deposition (MOCVD) which is at least US$1 million per unit machine. It is estimated that the initial startup cost of a White LED fab is around US$20-$30 million.

Second, it is not enough simply to have White LEDs on wafer. These White LEDs need to be cut out and mounted in a housing. In the LED industry, this mounting is called "packaging". For display applications, the packaging itself is fairly complex and expensive - perhaps as much as or more so than the LED chips.

Finally, there are variances in the performance of individual LEDs in a batch. As a result, LED packaging companies sort out White LEDs into different groups according to their respective quality - an activity called "binning." For illustration, if the application requires high performance White LEDs which is the case for display applications, the customer is likely to pay extra for each unit because the yield on high performance White LEDs is usually low (5 to 10% in each batch). To avoid paying this premium, most companies tweak their designs so that they can use at least some of the middle- or low-performance LEDs in a batch.

4.2 Cost

The cost calculation is mainly depends on the backlight design and the luminance. In LCD TVs (which would generally use RBG LEDs instead of white), current backlight designs are particularly inefficient, using several hundred individual LEDs to replace 12 or 16 CCFL bulbs. As a result, the increase of cost in adopting LEDs is several times the cost of CCFL. Therefore, without a significant change in the backlight design, it is unlikely that the White LED backlight will be dominant in LCD TVs soon.

CCFL backlights require an inverter for each CCFL tube when the device is DC powered (Direct Current, powered by battery); the cost of the inverter can equal or exceed the cost of the CCFL. While White LEDs do not require any inverter when the device is DC powered, hence the cost of the inverters can be saved and a significant power saving comes from getting rid of the inverters too. This is usually the case for smaller and portable devices, such as mobile phones, which explains the dominance of White LED in handheld devices. Nevertheless, this is not the case for LCD TVs and monitors which are mostly AC-powered (Alternating current) since no inverter is required for CCFL when the device is AC-powered.

Looking from another perspective, let us assume that a White LED costs around US$2 and a CCFL also costs US$2. For small display like cell phone displays, assume that two White LEDs are required (typically one to four White LEDs), hence the total cost is US$4. By comparison, a cell phone needs one CCFL and one inverter (assuming US$1.50), hence the total cost is US$3.50. Therefore the cost difference is small.

For LCD TV backlights, usually RGB White LEDs are being used. RGB White LEDs come in a group of four which consists of one red, one blue and two green (green has low brightness). For a typical 32 inch LCD TV as shown in the diagram below, the amount of White LEDs needed is one hundred fifty which is much greater than the sixteen CCFL needs. As a result, the cost of CCFL design is only one third of the cost of White LED design.

The above two simple illustrations show that why White LED dominates the small displays market while having great difficulty in penetrating the large displays market due to inefficient backlight design which results in high cost.

4.3 Simple case analysis by using ScGaN

Light Source Size		CCFL 32"W	EEFL 32"W	LED 32"W	FFL' 32"W
Lamp	CCFL # or LED #	16	20	150	1
	Unit Price	$2	$2	$2	$42
	Total Price	$26	$32	$270	$42
Diffusion board	for direct type	$11.2	$11.2	$11.2	$11.2
Diffusion sheet	Normal	$7.8	$7.8	$7.8	$7.8
Reflective sheet	Normal	$6.0	$6.0	$6.0	
BEF	BEF3 RBEF BEF2 DBEF	$10.7	$10.7	$10.7	$10.7
Metal Bezel Backt		$8.5	$8.5	$8.5	$8.5
Key Materials Subtotal		$70.6	$76.6	$314.2	$80.2
Others Materials Subtotal		$8.8	$7.8	$25.0	$6.0
BOM Cost	USD	$79.4	$84.4	$339.2	$86.2
L.O.P.,SG&A, Package	USD	$10.0	$8.0	$8.0	$7.0
Total Cost (w/o Inverter)	USD	$89.4	$92.4	$347.2	$93.2
Inverter Cost	USD	$28.0	$12.0		$10.0
Total Cost (w/h Inverter)	USD	$117.4	$104.4	$347.2	$103.2

Figure 4.2 Cost breakdown of typical 32 inches LCD TV [1]

The above table is a rough breakdown of cost for a 32 inch LCD TV. It can be seen that the cost of using White LEDs as the backlight is about three times greater than the other technologies.

It is reasonable to assume that the fabrication cost of ScGaN based White LED is about the same as the above mentioned GaN based White LED since ScGaN is built on the GaN based technology by introducing Sc into GaN for bandgap engineering.

By using ScGaN based White LEDs, the amount required will be less since the luminance of ScGaN based OYGB (>70 lumens/watt) is better than the any other current approaches. Assuming the above LED technology's (RGB approach) luminance is 50 lumens /watt, and assuming a linear relationship among the required number of LEDs and the luminance, using ScGaN based OYGB approach the required number of LEDs will be reduced to around 105 units. This reduction will be even greater as the size of the LCD TV increases. Therefore the reduction in cost will be around 45xUSD2 = USD90.

If the LEDs are made of phosphor coated blue LEDs, and assuming the total number of ScGaN based LEDs required is around 150 (the reduction in LEDs due to higher luminance will be offset by the fact each unit of OYGB LED has 3 more LEDs than the phosphorus coated blue LED), there will be a cost reduction due to the cost of phosphorus. It has been known that Nichia holds the patent of phosphor coated blue LED technology and assuming Nichia gets 3% of each LED being sold, the cost of phosphorus in each white LED is about 17% of the overall cost (This estimation is made by comparing the price of various white LEDs with corresponding blue LEDs). Therefore by using ScGaN based OYGB approach, the cost saving will be around 150 x USD(2x0.2) = USD 60.

The above calculations have shown that ScGaN based OYGB approach is able to reduce the cost of White LEDs backlight. The saving in cost will be greater as the LCD TV size gets larger. But it is still not enough to compete competitively in terms of cost with other current technologies unless a cheaper manufacturing method can be found to fabricate GaN based White LED. The good news is the current trend of White LED shows the luminance and efficiency are improving about 30% per year and the price is declining 10% per year. This makes it less and less of a premium to make notebooks thinner, or improve LCD TV performances. At this rate, it is projected that the White LED backlights will become a significant force in the large format LCD in 2010.

Reference

[1] http://www.displaysearch.com/free/

Chapter 5

Conclusion

5.1 The major players

The current major players in White LEDs are located at United States, Japan, Europe, Taiwan, and South Korea. Among all, the heavyweight LED manufacturers are Nichia, Osram, Toyoda Gosei, Cree and Lumileds. The White LED key patents are involving the use of phosphorus in order to generate white light.

Currently Lumileds and Cree have invested substantial amounts of money into the development of White LEDs as large format LCD backlights. Nevertheless, their technologies are still based on phosphorus which involves significant intellectual property issues. It is clear that the ScGaN based OYGB approach has the advantages of better luminance, and lower cost as compared with the phosphorus based White LED backlight solution.

The white LED world is a minefield of patents, cross-licensing agreements and infringement lawsuits involving the big five manufacturers. This can prove extremely daunting for new players entering the field.

The differences among the key patents are the choice of phosphorus being used (Appendix A). Therefore, the ScGaN White LED which can emit yellow or orange light through bandgap engineering avoids the complicated and messy intellectual property world of phosphorus based White LEDs. The main priority now is to apply patent for this ScGaN White LED and build a series of protecting patents such as the patent for fabricating a ScGaN film around it.

5.2 Business

Due to a host of developments and improvements as mentioned in the brief history of LED, the current LED technology is rather mature. It is believed that the White LED backlight technology is near the take off point and the ScGaN based OYGB approach will be a major push for this. Nevertheless, at the present time, the White LED backlight technology still has major concerns of cost and luminance as compare with other competing technologies.

It is believed that the cost will eventually be competitive to other competing technologies as well as the end users will realize that the performance of White LED backlight is much superior as compare to competing technologies. Last but not least, White LED backlight is a green (environmentally clean) technology.

A practical business strategy is developed here by first considering the amount of initial capital investment required by setting up a White LED fab. As mentioned the startup cost of a manufacturing facility requires a minimum investment of US$ 28 million. This has not taken into account the material costs, labor costs and so on. Therefore to raise US$ 28 million to introduce an unproven technology into an established backlight market is difficult.

First, let us assume a prototype of ScGaN based OYGB approach backlight will be built. The packaging procedure will be carried out in an existing LED packaging company or supporting research institute. The prototype should achieve all the claimed performances. Based on this prototype, survey and interviews will be carried out among LCD TV manufacturers. Utility chart of Lumens/watt versus Cost will be produced for future outlook and a demand analysis will be done. Below are the examples of utility chart and demand analysis. These preparations are important because the entry of ScGaN based White LED into the large format LCD backlight world as an unknown and unprepared player competing against mature players like the CCFL with well established distribution networks would mean minimal survival chance.

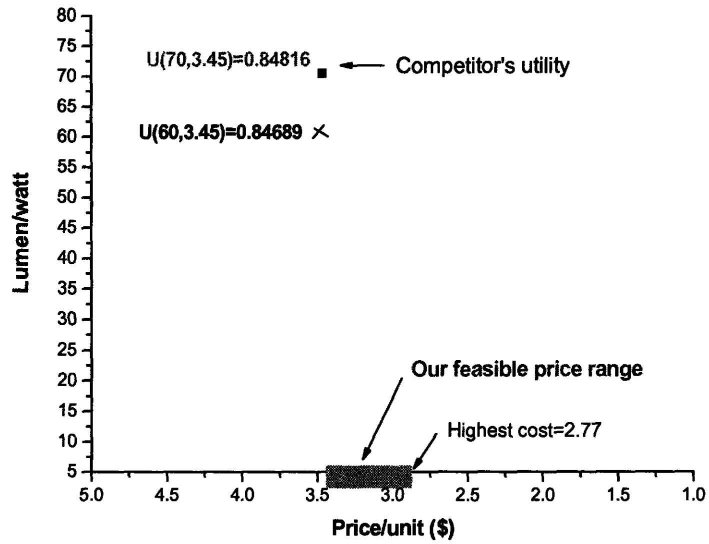

Figure 5.1 Fictitious Pricing analysis based on the utility chart

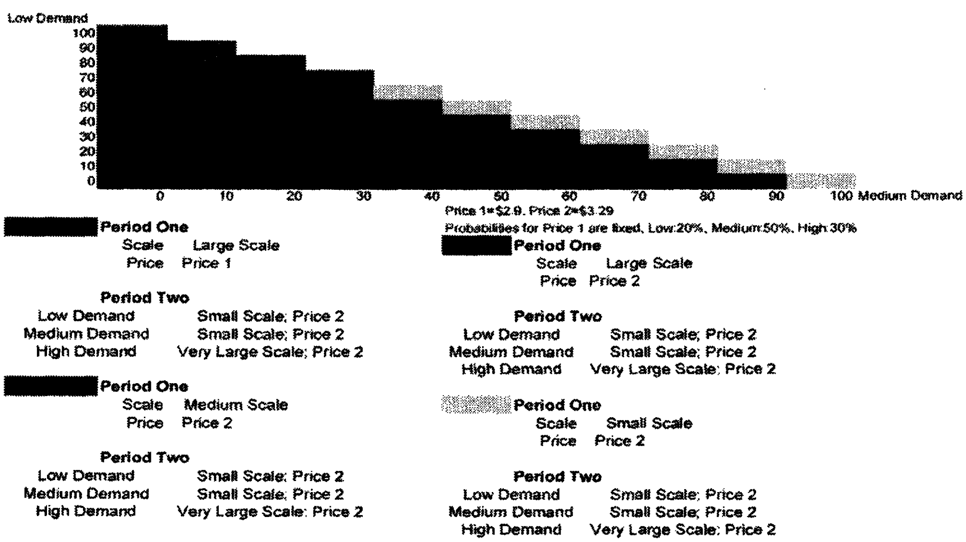

Figure 5.2: an example of Demand analysis based on course 3.57 by Prof. Clark with fictitious prices

If the first stage market research results are satisfying, these data can be used to convince the venture capitalists for initial capital investment. Three models are possible: 1) build a manufacturing fab, 2) fabless model and 3) Intellectual Property (IP) model.

The first model of building a fab involves high risk because of the very high initial capital cost. Entering the mobile screen market which is currently the largest market for White

LED backlight (US$ 3 billion market with 10% or market growth annually) to generate volume of sales and considerable amount of revenue initially can lower the risk in this approach substantially. Besides, the process flow of manufacturing ScGaN based White LED can be optimized while waiting to be adopted as the backlight of large format LCD in the near future. In doing so, it serves the purpose of getting first mover advantage as well as understanding the distribution channels of the White LED market.

The second model or fabless model where ScGaN based White LED production is outsourced to an existing fab like Chartered Semiconductor in Singapore for a fee. There are several advantages in outsourcing production to an existing fab facility. First, the initial capital investment required is much lower, therefore risk is minimized. Second, small volume production for initial market penetration via product demonstration is possible. Third, the fab will help to optimize the ScGaN based White LED manufacturing process.

The third model of IP model (licensing) is feasible because the ScGaN based White LED is based on the current GaN manufacturing process. Therefore, the leading manufacturers like Lumileds and Cree will be willing to incorporate this improved technology into their current backlight manufacturing line after the ScGaN based White LED is proven to be superior than their technologies. In fact this model can be combined with either the first model or the second model to maximize the profit. Besides, by forming partnership with companies like Lumileds and Cree which have an established distributor network as well as strong regional and global presence helps to boost the status of ScGaN based White LED too.

In fact, combining the fabless model and the IP model would be a good business model too; if the LCD TV market and the ScGaN based OYGB backlight take off in the near future, the business model can evolve into the fab model for greater profit margin.

5.3 Conclusion

The success of White LEDs in LCD TVs and large format displays lies on how fast its cost can be reduced and its luminance can be increased in order to compete with the other backlight technologies, how fast the LCD TV market is going to take off, as well as the attitude of the end users towards green, better performances technology versus the issue of cost.

The domination of large format LCD backlighting by White LEDs is likely to be just a matter of time.

Appendix A

The current White LED key patents all involve the use of phosphorus in order to generate white light. Below are some of the key patents (US based unless stated):

2628404 (Japan)	Covers the key technology that generates the high-quality emitting layer of blue LEDs and violet lasers. (Nichia)
6,600,175	A single LED with a down converting phosphor (Cree, 1996)
5,998,925	GaN LED with a garnet-based phosphor (Nichia, 1997)
5,847,507	A wide range of phosphors included (Agilent, 1997)
6,245,259	A blue, green or UV LED with a cerium or terbium doped garnet or sulphur substituted garnet phosphor (Osram, 2000)
6,809,347	Blue or UV LEDs with alkaline-earth orthosilicates doped with Eu phosphors (Toyoda Gosei, 2000)
6,501,091	Quantum dot phosphorus based LED (Hp and MIT, 2002)