FINE-GRAINED DYNAMIC VOLTAGE SCALING ON OLED DISPLAY

by

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Organic Light Emitting Diode (OLED) has emerged as a new generation of display techniques for mobile devices. Emitting light with organic fluorescent materials OLED display panels are thinner, brighter, lighter, cheaper and more power efficient, compared to other display technologies such as Liquid Crystal Displays (LCD). In present mobile devices, due to the battery capacity limitation and increasing daily usage, the power efficiency significantly affect the general performance and user experience. However, display panel even built with OLEDs is still the biggest contributor to a mobile device's total power consumption. In this thesis, a fine-grained dynamic voltage scaling (FDVS) technique is proposed to reduce the OLED display power consumption. In bottom level, based on dynamic voltage scaling (DVS) power optimization, a DVS-friendly AMOLED driver design is proposed to enhance the color accuracy of the OLED pixels under scaled down supply voltage. Correspondingly, the OLED panel is partitioned into multiple display sections and each section's supply voltage is adaptively adjusted to implement fine-grained DVS with display content. When applied to display image, some optimization algorithm and methods are developed to select suitable scaled voltage and maintain display quality with Structural Similarity Index (SSIM), which is an image distortion evaluation criteria based on human vision system (HVS). Experimental results show that, the FDVS technique can achieve 28.44%~39.24% more power saving on images. Further analysis shows FDVS technology can also effectively reduce the color remapping cost when color compensation is required to improve the image quality of an OLED panel working at a scaled supplied voltage.

TABLE OF CONTENTS

LIST OF FIGURES

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The past two years are the most meaningful time of my life so far. When I started my master degree, I left my original major of Automation behind and try to learn some new things about Electrical and Computer Engineering including hardware design, architecture and embedded system. The beginning was a tough and frustrating process, from which I suffered a lot, but also learned a lot. It's so delightful that, there are so many people teaching me, helping me and trusting me. I am always lazy and lame, but there are also some people pushing and threating me to become a hard worker sometime (especially before deadlines).

After two years of struggling, I grow up from "knowing nothing" to "knowing something", but still far away from a qualified researcher or technician. I am so glad that I can continue study as a PhD. as a poor amateur under Professor Chen's advice to polish my knowledge and skills in following years.

I am very thankful to Dr. Steven P. Levitan, who is one of my most respectful professors. And lots of thanks go to Dr. Jun Yang, who gave me valuable suggestions. I am so grateful for their kindly consent to be my committee members. Thanks my collaborators and our research group in University of Pittsburgh.

Thanks my parents, who support my back and smooth my heart. They are the most motivation to me in this world. And thanks to my friends, they suffered enough of my complaint.

1.0 INTRODUCTION

With the organic light emitting diode (OLED) display technology's fast development and its increasing application to present mobile devices, more and more researches are focusing on OLEDs display performance and power efficiency. With limited battery capacity and increasing daily usage, power optimization becomes a primary issue to improve the mobile device performance and user experience. Although OLEDs can significantly improve the display power consumption compared to other display technologies such as liquid crystal display (LCD), the display panel even based on OLED technology is still one of the biggest power consumers in a general mobile device. This thesis presents a systematic optimization method facing to OLED display power optimization. It covers several aspects of OLED technology from bottom level of driver circuit design to high level of graphic processing algorithm.

1.1 BACKGOUND

Current mobile devices become much more popular than ever in peoples' daily life. The general definition of mobile devices is also extended from cellphones into portable game consoles, tablets, laptops and other new electronic products. It is so amazing that the cellphones in past ten years have evolved from merely communication featured into multimedia platforms equipped with mature smart operation system and high end hardware configuration. Until 2012, the

ownership of smart cellphones in USA has grown to 54.9% from less than 30% in 2010 [53]. Correspondingly, as the most important role for human-computer interaction, the display technology also achieved tremendous success in this explosive growth of multimedia mobile devices. For example, report indicates that the mobile OLED display increased to from 19 million units in 2011 to 150 million units in 2012 [54]. And the display quality and power efficiency also becomes a considerable criteria to compare the general performance and user experience between different mobile devices. In this process, different display technologies have also experienced significant evolutions featured with display area, pixel density, color accuracy, contrast ratio, luminance strength and power efficiency.

Display's power efficiency also becomes quite important. Although the power consumption distributed into network communication and computation increased significantly with technology evolutions, display screen still accounts as the biggest power consumer in a mobile device. This power consumption also varies with different display technologies.

LCD is the most popular display technology right now. Based on modulating backlight units' (BLUs) projecting light and filtering spectra with liquid crystals, LCDs outstand with brightness and thinness. It's widely adopted by most powerful mobile devices producers like Apple, HTC and Motorola for cellphones and laptops. However, LCDs greatly limit the battery lifetime of the mobile devices due to low display power efficiency. According to research report, the LCDs in laptops occupy the total power consumption of 30% [2]; while in mobile devices, this percentage raises up even to more than 60% [3]. Some other display quality issues also exist in LCDs such as view angles, brightness under sunlight, contrast ratio and panel flexibility.

Overcoming some disadvantages of LCDs, OLED technology is becoming more popular than ever. With promotion from powerful companies such as Samsung, LG and AUO, OLEDs are

widely applied into cellphones and tablets in recent years. OLED display is based on the fluorescent light emitted from a series of chromatic organic materials between electrodes. When current is applied, bright fluorescent light will be emitted from those organic materials. And with different dopant, those organic materials will generate different colors. Since OLEDs emit light by themselves and do not require any BLUs, which is the primary power consumer in LCDs, OLED panels are much thinner and more power efficient than LCDs.

Compared to LCDs, the advantages of OLEDs are: 1) Lower power consumption. As OLEDs' light emitting does not depend on BLUs, the power consumption is much less. In recent report from LG, OLED TVs power consumption is supposed to be around 30% about a typical LCD panel [6][7][8]; 2) Higher display quality. The chromatic colors produced from OLEDs are fluorescent light directly emitted by the organic materials. The organic fluorescent materials will introduce higher contrast ratio, wider view angles and better luminance performance against sunlight [9][10]; 3) Faster refresh rate. As the OLEDs are directly controlled by the current flow through the organic fluorescent materials, the OLEDs display programming is much easier to control and faster to implement [11]; 4) Flexible display panels. Both LCDs and OLEDs have to be manufactured based on specific substrate. Different from glass based LCDs; OLEDs can be built on plastics, which are thinner, lighter, and cheaper. With flexible plastic substrate, OLED display panels can be even made into different shapes and curves. And with transparent thin film transistor (TFT) driver circuits, the OLED panels can be made even transparent [12][13][17].

Definitely, OLEDs aren't perfect. First of all, it costs more to produce an OLED display panel than it does to produce an LCD panel, although this should hopefully change in the future, as OLEDs has a potential to be even cheaper than LCDs because of their simpler design [14]. OLEDs have limited lifetime, which was quite a problem a few years ago. But there has been

constant progress, and today this is almost a non-issue [15][16]. Lots of OLED panels are also developed to compete with LCDs in display area and pixel density.

Moreover, the power consumption problem still exists in OLEDs. Unlike LCDs whose power is primarily consumed by BLUs, OLEDs' power consumption is decided by the colors tuned in each pixel. In a single OLED, that generates specific color, the added dopant to organic materials affects the luminance and power characters. Also, since an OLED pixel is composed of several different monochromatic OLED cells (or sub-pixel), and use particular luminance combination to produce chromatic colors, the power consumption will also vary a lot with colors. For instance, the power consumption of an OLED pixel displaying "black" is only around 40% of a LCD pixel, whose power consumption is constant in different colors. This is because almost no current is necessary to pass the organic materials to produce any light. However, an OLED pixel displaying "white" consumes almost three times power of a LCD pixel because all emissive layers are used simultaneously [17][18]. When the colors are tuned in RGB color space, external quantum efficiency values of 20% and 19% have been reported for red and green diodes, respectively [20]. Power difference also exists in different colors, blue OLEDs have much lower power efficiency than red and green ones [19]. Hence the luminance mechanism is much more complex than LCDs, and OLED display power management becomes essential in the battery-powered devices, such as mobile cellphones and laptops [21].

1.2 MOTIVATION

As an emerging display technology, OLEDs have been well promoted into practical mobile devices with increasing market share. Behind this fast development, more than 10 years of

dedicated researches have been invested in organic material, pixel arrangement, and manufacture process. These researches are mainly focusing on increasing OLEDs' display quality, accuracy and area to apply in devices application. Meanwhile, other research focusing on peripheral driving method, power efficiency, and system level optimization are still remained immature, compared to other display technologies such as LCD.

As presented before, the power efficiency might be one of the most direct issues to improve the general mobile device performance and user experience. The basic idea behind this thesis is to implement dynamic down scaling the display panel's supply voltage and hence reduce the general power consumption. However, in conventional OLEDs, color will be distorted significantly when big down scaling is applied to supply voltage. Hence, modifying the OLEDs driver circuits to create more voltage scaling space without luminance distortion is the first key to achieve DVS and power saving. Also when applied into higher level of display panel, how to make most advantage of the DVS with different display content is another challenge. And when the voltage is applied into the display panel, how to evaluate and maintain the display quality is also an important issue to system level optimization.

In this thesis, I am focusing to build up such a system solving these problems. New driver circuits are designed with a series of simulations; image analysis and quality evaluation are studied to develop suitable scaling algorithm and optimization method. Evaluations are made to prove the efficiency of proposed techniques.

1.3 PREVIOUS WORK

Since power saving technology in OLED display panels is not fully developed in previous work, some ideas are derived from LCD voltage scaling techniques. Right now, DVS methods are already applied into LCDs, where the BLUs are dimmed to save power. This section will review these cases to present the mature concepts of display DVS techniques. Also previous display technologies in OLEDs are also introduced, including modeling, power analysis and some DVS related research.

1.3.1 LCD Voltage Scaling

A typical LCD panel is composed by multiple layers, such as BLUs layer, liquid crystal layer, filters and substrates. A basic LCD display panel diagram is shown as in Figure 1.1. Among those layers, the function core is liquid crystal layer, which is used to tune the chromatic color spectra and monochromatic grey levels [4]. In this layer, liquid crystals are aligned between two transparent electrodes and polarizing filters. If there is no liquid crystal angle change, the light will be blocked from the chromatic polarizing filters, hence no color luminance will be released and the color will be black. However, when an electrical field is applied to the crystals, the angle of the crystals will be changed to form a particular light path. By controlling the voltage applied across the liquid crystal layer in each pixel, light strength can be tuned to different gray levels. With more complex crystal alignments and color filter films, the LCD panels can be made with specific pixel matrixes and produce chromatic colors [22].

In LCD panels, the amount of light perceived by human eyes depends on the color intensity, which is controlled by the liquid crystal transmissivity t, and BLUs light strength level b. The

perceived luminance L is a product of the transmissivity t, which can be also seen as the pixel gray level (i.e. 255 in RGB color space) and the light strength level b. Different color luminance will direct affect the color tuning and display content.

$$L = t \cdot b \tag{1.1}$$

The power consumption disadvantage in LCDs comes from the inherent light emitting mechanism. In LCDs, the liquid crystals won't emit any light and BLUs are required as extra light sources. The BLUs are mainly made by cold cathode fluorescent lamps (CFLs) or light emitting diodes (LEDs). Typically they have to produce constant light with considerable power consumption, leaving luminance strength and color tunings to liquid crystals and filters.

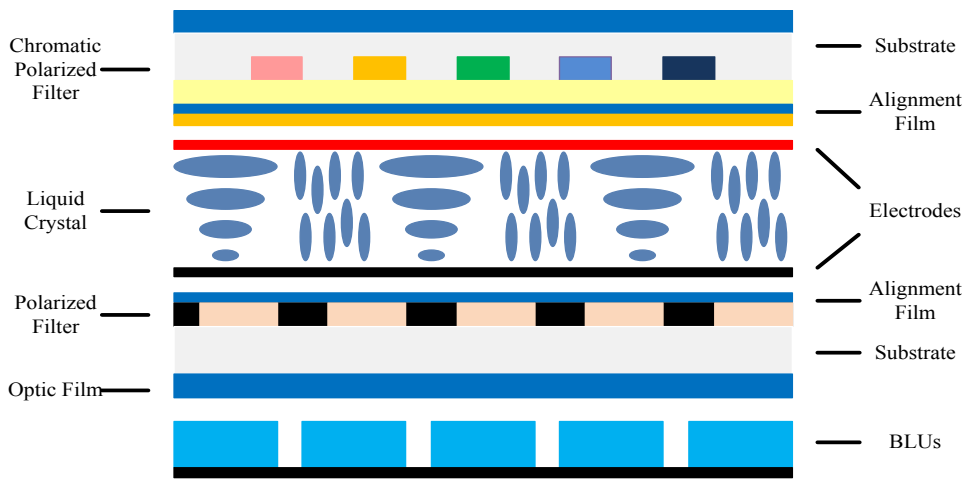


Figure 1.1 LCD Panel Structure

To reduce the power consumption, some dimming technologies have been developed to lower the BLUs light strength levels also with power consumption in dark environment. While, if the BLUs levels were changed, the whole display panel will be dimmed with a single dimming factor [21][23]. And the luminance perceived by human eyes will be directly affected. This method of voltage scaling is referred as global dimming. Global dimming under dark environment or shutting off the display BLUs automatically after a certain time of no-operation, have already been widely adopted in present LCD devices. However these methods still can't

reduce the power consumption of display during normal display operation. In some more complex solutions, the BLUs dimming are not only associated with environment but also with the display content dynamically. Since an amplify factor contrast to the BLUs dimming can be applied to the transmissivity t, luminance L can be well compensated with dark display content. Hence the power consumption in BLUs can be also trade off by scaling down supply voltage dynamically with display content on runtime, and the display quality can be maintained.

Nowadays, LEDs replaced CFLs to work as BLUs, which make dynamic local dimming possible. In LEDs based LCD panels, the LED bulbs are aligned as matrix under the liquid crystal layers. And each LED bulb can be controlled independently to achieve dynamic dimming for specific display area. Correspondingly, the display content on the LCD panel is virtually divided into multiple regions in order to adapt local content. If the DVS on BLUs is applied on some areas without visual focus, the dimming even with distortion may not affect human visual perception. And the dark region areas can be dimmed more aggressively than bright ones. Hence the local dimming can provide a chance to gain more power saving in LCDs [24].

1.3.2 OLED Voltage Scaling

Although the OLEDs are much more power efficient than LCDs, they are still very power consuming comparing to other components in a mobile device. In Table 1.1, I analyzed some display power consumption with video streams played with Galaxy SIII, which is an OLED cellphone produced by Samsung. In total power consumption, the general power consumption is evaluated including CPU, GPU process, network communication, memory access, decoding process and display screen. The contrast power consumption is evaluated from the contrast tests, which close the display screen. The values are averaged from 4 classifications from YouTube,

and each classification includes 50 video streams. The most power consumption comes from Sports, in which, the OLED screen consumes 29% in 60fps and 32% in 30fps. In Sports videos, bright color tone and complex textures requires high luminance and balanced color tuning, which introduce much power consumption into the display panel. While the least power consumer is music video, which generally adopt dim light sources, only 15% in 60fps and 17% in 30fps. From the table, we can tell that: OLED display is quite display content dependent; when the display contents fulfill the display screen, the display will directly affect the general power consumption; if we can aggressively dim the OLED screen in some areas, the power can be significantly reduced.

Table 1.1 Display Power Consumption on Video Stream (*mW*)

Total Power Consumption

Video	1280x720		640x360 (full screen)		640x360 (original size)	
	30fps	60fps	30fps	60fps	30fps	60fps
Music	786.4	975.8	682.9	783.7	594.9	698.1
Sports	960.4	1172.1	855.3	953.2	652.4	751.9
Game	869.0	1061.2	786.5	889.1	628.2	730.8
Politics	901.3	1124.3	802.7	915.7	612.3	725.5

Contrast Power Consumption

Video	1280x720		640x360 (full screen)		640x360 (original size)	
	30fps	60fps	30fps	60fps	30fps	60fps
Music	646.9	820.8	543.8	648.2	544.8	649.4
Sports	646.8	823.2	542.5	644.3	548.7	649.0
Game	644.3	820.6	543.5	643.7	548.0	648.8
Politics	647.5	822.1	545.2	644.2	548.2	649.0

With discoveries in practical measurement, it is optimal to apply dimming mechanism into OLEDs, which might be achieved by DVS. However, when DVS is applied into OLEDs' supply voltage, the displayed luminance will be directly affected. Hence color fix or color compensation becomes a very important part of OLED DVS and power saving. Moreover, since an OLED pixel's power consumption is positive correlated with the color displayed, the balance between DVS and compensated color will also become a problem.

In some mobile devices, especially those heavily emphasize the operating systems, UI colors are mainly designed with low power consuming colors like black and green, while some high power consuming colors like white and blue are avoided [21][25]. However, in this solution, the user experience is highly defected and power saving won't achieve with arbitrary display content.

Similar with the dimming technologies from LCDs, global DVS was also introduced to OLED power management to adjust the display panel luminance [24][27]. DVS is globally applied into early OLED designs, which have less voltage scaling space and color distortion tolerance. But those proposed methods can't be adopted into present OLED with complex designs and large display panels. Also HP Lab proposed to dim the non-visual focal area in the image for OLED power saving [26]. In their research, some peripheral parts of the screen, for example, black sides of movies, unselected menu items will be dimmed. Different from color remapping or global DVS, this technology will directly adjust the specific display area's OLEDs supply voltage and reduce the color density hence the power consumption. However, it is hard to distinguish whether a display section is visual focal or not, and there must be considerable power overhead in image processing computation like edge detection [28][29][30].

1.4 CONTRIBUTION OF THIS THESIS

Focusing on the circuit design, image processing, and image quality evaluation, this thesis gives a new solution to OLEDs' power saving. Compared to the existing works, this thesis's contributions are:

(1) A new OLED driver design is proposed as DVS-friendly OLED driver. This OLED driver design can effectively maintain the color accuracy when supply voltage is scaled down, as long as the required luminance of the OLED cell is within the specific threshold.

(2) The DVS performance is well evaluated, considering the relationship between voltage scaling and the color distortion. The DVS-friendly driver's performance is evaluated along with conventional driver design.

(3) Fine-grained DVS is proposed in OLED display panel. The display panel is virtually divided into multiple sections with independent voltage regulator to dynamically adapt the supply voltage with display content and achieve aggressive voltage scaling.

(4) Corresponding voltage selection, display quality control algorithms are proposed. Based on human virtual perception image quality of the OLED displays index, i.e., Structural Similarity (SSIM), lots of image processing simulations are made to evaluate DVS affect to color distortion, display quality and color compensation cost.

(5) A series of experiment are made to evaluate the FDVS performance. The experiment results are compared with those of previous works to evaluation its effectiveness and advantages.

1.5 SUMMARY

In this chapter, some display technology basics are introduced, including LCD and OLED. Also the advantages of OLED over LCD are presented in several aspects, especially for color tuning mechanism and power saving efficiency. Technologies issues are emphasized in the display power saving research like color tuning and voltage scaling, which are derived from LCD technology. The key idea to realize the OLED power saving is particular driver circuit and corresponding regulating method. Based on the proposed research, the contribution of this thesis is summarized.

2.0 DVS-FRIENDLY OLED DRIVER DESIGN

In last section, the basic concepts of the OLED technique and dynamic voltage scaling have been introduced. As presented before, one of the most important key to explore the potential of DVS in power saving is to reduce the color distortion introduce by down scaled supply voltage. To achieve this goal, one of the most direct ways is to improve the driver circuit to be more resistant to color distortion when the supply voltage is scaled. In this section, the OLED cell structure and color tuning mechanism will be studied and the modeling of OLED will be built for later simulation. Also, several typical kinds of OLED pixel driver circuits will be discussed. Based on those studies, my own circuit design is proposed. Simulations are made to prove it is more suitable to OLED DVS.

2.1 OLED CELL

OLEDs' lighting mechanism is totally different from other display technologies, such as LCD. In a display image, the most basic display unit is a screen pixel. And a pixel might also be composed of different cells (or sub-pixels) according to color space or specific quality requirement. In a typical OLED pixel, several OLED cells emitting different colors are aligned together to form RGB color space. The OLED cell details will be presented in this section including physical structure, modeling, and performance characterization.

2.1.1 OLED Cell Development

An OLED cell is a stack structure of organic fluorescent layer, electric transportation layer and electrodes. The organic emissive layer, which contains organic fluorescent materials, is sandwiched between a hole-transport layer and an electron-transport layer. Directed by transportation layers, electrons and holes are captured in the emissive layer to produce fluorescent light. The fluorescent luminance strength can be modulated by the electric density in the organic emissive layers. Also, with different metal dopants, the fluorescent light can perform different colors.

In past few years, monochromatic OLEDs are mainly in mobile players, instrument panels and other small display screens. With advantages of OLEDs' low power consumption and high contrast, the display performance is highly improved than LCDs. In these OLED products, the cell structure is mainly based on a single layer of monochromatic OLED materials without any complex color tuning or sub-pixel matrix design.

Similarly, people are also trying to build pure white lamp with OLEDs, which can have better power efficiency than CFLs and can be made flexible and transparent. However, there is no single dopant for OLED to produce pure white light. The technician from Phillips aligned yellow and blue OLED strips alternately with each other to build a white OLED lamp. Covered with light mix glass, the alternating two different color OLEDs can produce white similar color. The cell structure of those lamps is just based on signal layer of monochromatic organic materials of huge area [31][32]. Later, a complex cell structure design is introduced by the OLED lamp design. Universal Display Cooperation (UDC) announced their new white OLED lighting panels. The new panel design used a Stacked-OLED (SOLED) architecture, which just stack the different color OLED cells rather than align them one by one [28][33]. Right now,

some monochromatic OLEDs are also applied as LCD BLUs or other signal bulbs and the OLED lamps are still promoted hardly by many companies. While, OLEDs achieved much more aggressive for chromatic display, and evolved with more complex chromatic tunable cell structure.

As the basic component unit of a chromatic display screen, a color tunable OLED pixel is composed of three basic colors as RGB color space generally. In RGB color space, a chromatic pixel is composed by different sub-pixels (red, green and blue) composition. To form the RGB chromatic pixel with OLED materials, there are lots of trials. For example: some people use blue light to filter out white similar light. Then, with color pass band polarizer and filters, the white similar light is down-conversed to green and red light [32][33]. And these colors will compose the chromatic pixel arbitrarily again. This idea of color filter is very similar with LCDs'. And the OLED cells in these panels are all the same. But nowadays, most people are directly adopting RGB OLED cells as sub-pixels to tune colors. That means each OLED pixel will be composed with at least three kinds cells. The techniques also vary on how to arrange the R, G, B cells in structure level. Some take the advantage of luminance efficiency difference. In this design, different color layers are stacked vertically, with high luminance efficiency color in the bottom. This design can to make better color mix and reduce the pixel area to improve pixel density [27][29][33]. But this method requires higher manufacture cost and the product performance is not quite stable.

The most popular design is still to align the three cells in a line to form a pixel. The discrete cells of red, green and blue are aligned side-by-side, sharing same voltage supply and substrate. However each cell in a pixel will be controlled by independent driver circuit and will be programed to tune different colors. In Samsung's recent years of OLED products, the sub-pixel

matrixes have different designs in each generation. Earlier products, like Super AMOLED are using PenTile matrix, which using G-R-G-B sub-pixel alignment. And other products, like Super AMOLED Plus, use LCD like R-G-B sub-pixel alignment, but each sub-pixel has same area [51][52]. Recently, in Super AMOLED HD, the designer is focusing to balance the OLED cells' color performance with specific area ratio. This design is widely adopted into the new Samsung products, like Galaxy Note2 and other tablets, which needs better display performance and bigger display area. The structure of such a RGB color tunable OLED pixel is shown in Figure 2.1. In this pixel structure, the R-G-B sub-pixels are aligned in the same layer with different area ratio.

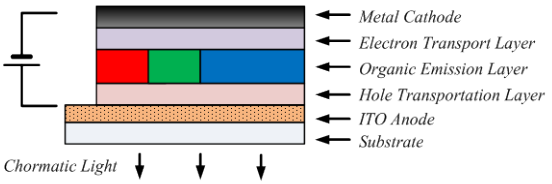


Figure 2.1 Structure of a Typical RGB Color Tunable OLED Pixel

In the view of color performance balance, firstly, the green light is most sensible to human vision while red and blue are much less; also, due to the disadvantage of material, the OLED material used to produce blue light degrades more rapidly than others [11]. So it's quite efficient to leverage the size of the R, G and B cells in a pixel to balance the luminance density and lifetime. With different areas, high efficiency cells such as greens can achieve sufficient performance with small area and less power consumption, while low efficiency cells such as blues can have less current density to reduce lifetime and larger light emitting area to increase its luminance. In the most recent OLED sub-pixel matrix design, a blue OLED cell may be 100% larger than the green cell. The red cell may be 10% smaller than the green [21]. In this thesis, the driver design is based on this cell structure, which can offer specific power model and luminance performance for the experiment.

2.1.2 OLED Cell Modeling

To further evaluate OLED cells power and display performance, accurate models of the OLEDs are required. To characterize the OLED cells, *I-V* (current-voltage) test are used to characterize the OLEDs after construction. *I-V* characteristic might changes with materials, size and OLED cell structure. However, the form of the *I-V* curve is quite similar for all OLED materials, which can be approximated by a parabolic or exponential function. Based on this *I-V* performance, the OLEDs show a specific *R-C* character. OLEDs have large area of organic material layers between the electrodes and the thickness is about 100-200 *nm*. This introduce significant internal capacitance [26][35]. The typical value of the internal capacitance C_{cell} is 200~400 pF/mm^2. Also a resistor is in series with the OLED capacitor. The resistance is internally from the organic material lays and the electrodes. Compared with the electrodes, the resistance from organic material layers is insignificant and the total resistance is mainly depending on the parasitic resistance from electrodes. The common material for electrodes is transparent indium-tin-oxide (ITO). Since the ITO layer is more or less fixes, the ITO resistance is given as square resistance and it has a typical value of R_{ITO}≈15 Ω/*sq*. An equivalent modeling schematic of an OLED cell can be seen in Figure 2.2. A LED is also included in the modeling schematic, which represents the light emitting function of the OLED cell.

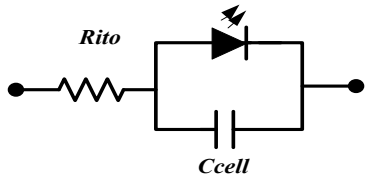


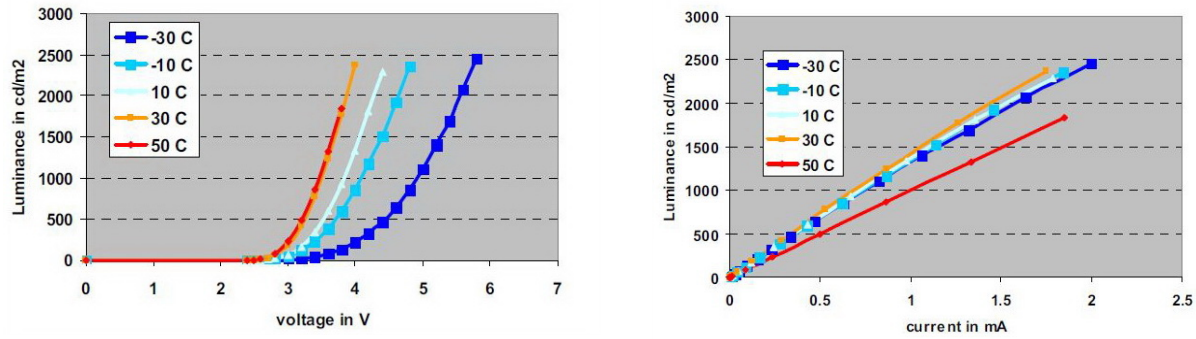
Figure 2.2 Equivalent Schematic of an OLED Cell

2.2 OLED DRIVING

Despite of the OLED cells, which consists sub-pixels and then the pixel matrix, a highly integrated OLED display panel consists of power suppliers, voltage regulators and selector switches for rows and columns. For a higher level view, the display panel is controlled by a MCU interface with current converters, timing controllers, graphic display data RAMs so on and so forth. When the display panel is working, graphic display data are bit mapped from static RAMs, and those data will be converted into voltage or current singles into the pixel driver circuit to program display content. In RGB color space, the display system is separated for three sets to control RGB color dimensions independently. That means each sub-pixel is driven independently. In OLEDs, the OLED driving methods and driver circuit design is totally specialized according to OLED's performance characters.

2.2.1 OLED Driving Methods

In OLED cell, despite of the color characters, which are determined by the metal dopants and sizes, the most important parameter of OLED cell is the luminance of the emitted light. Based on the *V-I* test and *R-C* characterization to model the OLED's performance; lots of *V-I-L* characters experiments are performed to study the link between the OLEDs' electrical performance and luminance strength. Here are two figures indicating the luminance change in a small molecule OLED display piece of a 20 mm^2 active area, with voltage and current in different temperatures respectively. The standard to evaluate the luminance efficiency is cd/mm^2. *cd* is an international standard to evaluate the light intensity. A common LCD TV can give luminance range from 450cd/mm^2 to 1000cd/mm^2 and a common OLED cellphone can give luminance about cd/mm^2.



(a) (b)

Figure 2.3 Characteristics of an OLED Cell with an Active Area of 20 mm^2:
(a) *I-V* character, (b) *I-L* character [26]

In Figures 2.3, the *V-L* character is non-linear and varies a lot with different temperatures. While the relationship between current and luminance is quasi-linear and does not depend much on temperature. The luminance suffers obvious distortion only at high temperature, but is still in linear relationship. Hence the best way to control the light output of the OLED is focusing on current modulating rather than voltage. With this control mechanism, the current through the OLED cell is the most important control object for an OLED driver.

From a control perspective, the OLED cell is usually programed by two different driver methods, namely, pulse-width-modulation (PWM) and amplitude-modulation (AM). In PWM method, switching discrete signals are applied to the OLED cells. With sequentially closing and opening the driver switch, specific pulse patterns are applied to adjust the OLED cells' luminance. However, with quick switching signals applied on the OLED cells, the internal capacitances will be quickly charged and discharged and the OLED cells will suffer huge current spikes. That will case lethal affect to the OLEDs lifetime. Additionally, since the PWM method is working on high voltage/current amplitude range to prevent the descending along circuits, the power efficiency is not good enough.

Rather than PWM method, the AM method is more preferred. In AM method, a constant current is applied to the OLED cell and maintained by its driver circuit. Only when the display

content is going to be changed, the OLED cells will suffer specific current change. The OLED cells will not suffer from huge voltage spikes and the lifetime can be much longer. According to different driving methods, different driver circuits are designed. And the driver circuit in each OLED cell will be more complex with AM method.

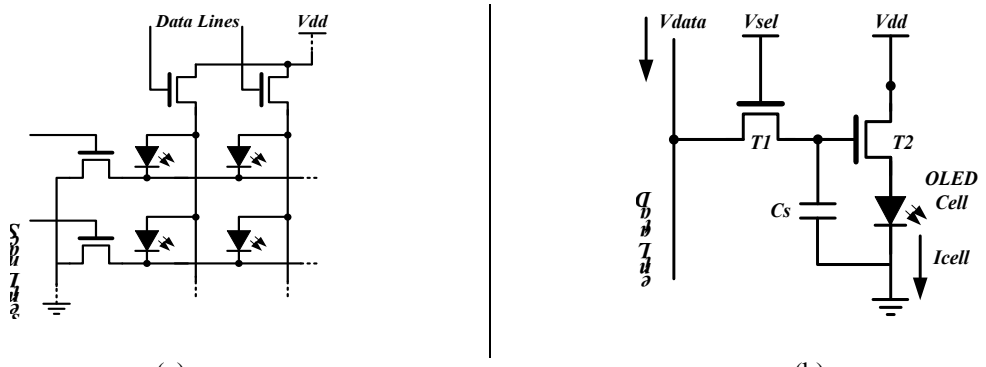
2.2.2 OLED Driver Circuit Designs

From a circuit perspective, OLED driver circuits can also be divided into two types, namely, passive matrix OLED (PMOLED) and active matrix (AMOLED). During display, each OLED pixel in the display panel is selected by turning on the selection transistors of the corresponding rows and columns. Then the display contents in display RAMs will be converted from bit map to the pixel programming signal with voltage or current regulators. And the signal regulators, which are designed for each color dimension, will program the OLED cells in selected row or columns simultaneously.

PMOLED is designed and adopted in the early OLED products. As shown in Figure 2.4 (a), the PMOLED driver circuit is quite simple, consisting of only transistor switches. However, this driver design cannot maintain the display contents effectively during refresh gap. When the pixels are not selected, the display content will only depend on the fluorescence effect, which will degrade significantly and cause incidental image. Also, the OLED panels require a constant and very fast refreshing rate to maintain the display content, which limits the OLED cells' lifetime. Additionally, the voltage drop along the column metal wires can be significant so that a high supply voltage (V_{dd}) must be applied to compensate the brightness of the pixels at the far ends of the array. This might introduce the non-uniform supply voltages on each pixels causes the severe color distortion issue when OLED panel size is large, i.e., bigger than 3-inch. Such a

design, not only cause quality problem, but also lowers the power efficiency of PMOLED circuits, shortens the OLED cells lifetime and limited the panel sizes. Nowadays, PMOLED drivers are only used in some small monochromatic display panels.

As the image quality trends to clearer, more stable and brilliant, power consuming needs to be reduced and display panel sizes head to huge resolution, the AM driver is preferred by more and more companies and users, even this perforation is requires more complex circuit design and more fabrication cost. A conventional AMOLED display driver circuit can be seen in Figure 2.4 (b).



(a) (b)

Figure 2.4 OLED Drivers Schematics: (a) Basic PMOLED Panel; (b) Conventional AMOLED Driver

In the conventional AMOLED design, the OLED cells driving current I_{cell} is supplied by a driving transistor T_2 whose gate voltage is programmed by V_{data} through a select transistor T_1. The display status of the OLED cell can be maintained by a storage capacitor C_s even after T_1 is unselected. Compared to PMOLED designs, AMOLED can maintain the OLED cells luminance without fast refreshing. That means, in contrast to PMOLED, AMOLED drivers can achieve better display quality, lower power consumption and no restrictions on either the OLED panel size or resolution.

V_{dd} is the drain voltage to T_2 and produce required current through T_2 to drive the OLED cell. The variations of V_{dd}, may result in the nonlinear change of I_{cell}. In other words, color distortions

occur immediately right after the V_{dd} is scaled (the simulation will be shown in later part). That means, if the DVS is applied into the driver circuit, the image quality might be reduced significantly. And this driver is not suitable with much voltage scaling for power saving. Also, when the supply voltage is scaled, some color compensation mechanism is necessary to rise up the voltage scaling space.

2.3 DVS-FRIENDLY AMOLED DRIVERS

To overcome said shortcomings from conventional drivers, a new AMOLED driver circuit is designed based on current amplitude, which is resilient to supply voltage variations. Since the design is proposed to be more suitable with the dynamic voltage scaling and power saving, this AMOLED driver is DVS-friendly as shown in Figure 2.5. Similar to conventional AMOLED driver design in Figure 2.4 (b), the display status of the OLED cell is programmed when V_{sel} is raised. A current mirror composed by T_1 and T_2 will provide stable and absolute equal currents to point A and point B. At the same time, V_{ctrl} is pulled down to turn off T_3 and ensure no other current flowing from V_{dd} to the OLED cell. Programming current I_{data} will directly passes through T_1, T_4, and the bias conditions of transistor T_4 is setup.

When V_{sel} is pulled down, I_{data} is cut off from the OLED cell. V_{ctrl} is raised to turn on T_3 and continue to keep the OLED cell working in refreshing period and emission period. Because the bias condition of T_4 is maintained by C_s, which is charged by I_{data}, the current through the OLED cell is unchanged (I_{cell}=I_{data}). When V_{dd} scales, I_{cell} keeps the same with I_{data} as long as the V_{dd} is high enough. In other words, color distortion occurs only when the V_{dd} is too low to supply I_{cell}= I_{data}.

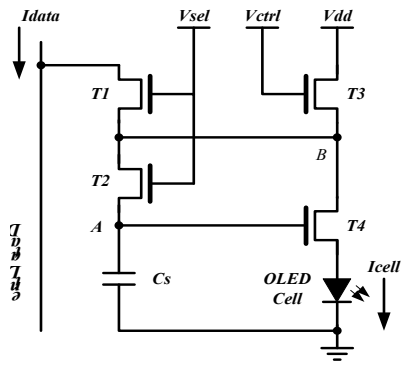


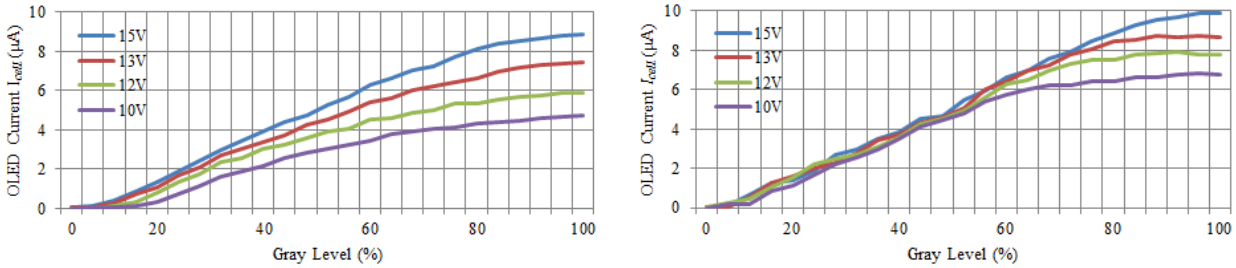
Figure 2.5 Schematic of DVS-friendly AMOLED Driver Design

Figure 2.6 depicts my simulation results of the relationship between I_{cell}'s and the programmed gray levels for both conventional OLED driver design in Figure 2.4 (b) and my DVS-friendly design. Gray level (horizontal axis) denotes the normalized programming signal strength over the maximum level. Actually, the gray level is a concept from the monochromatic image to indicate the black color luminance levels. Later people use this to indicate the image signal about luminance. In RGB color space, the absolute maximum gray level is 255. Vertical axis is I_{cell} whose maximum magnitude is 10 μA in DVS-friendly design.

Figure 2.4 (a) shows that in conventional OLED driver design, when V_{dd} reduces from the normal level $15V$, I_{cell} decreases substantially and directly causes color distortions. As shown in Figure 2.4 (b), in DVS-friendly design, I_{cell} shifts from the required magnitude only when the gray level is high. Even at the high gray levels, the degradation of I_{cell} is still much less than that of conventional OLED design.

Compared with the conventional AMOLED driver design, the OLEDs are directly programed by the current mirror, which makes the OLEDs' programming more precise and the capacitance charging more stable. When the supply voltage is scaled, the programing value maintains at the same value in some range. Moreover, when some image processing mechanism are applied to the image data in display RAMs, the processed output can directly applied in to the OLED currents

I_{cell}. In dynamic voltage scaling behavior, this driver can react faster and more precise than the conventional AMOLED drivers.



(a) (b)

Figure 2.6 Relationships between I_{cell} and V_{dd} of an AMOLED Driver: (a) Conventional Design; (b) DVS-friendly Design

2.4 CONCLUSION

In this section, the OLED technology is studied step by step from the cell structure, character modeling to corresponding driver designs. The OLED structure design is based on RGB space and each OLED cell can be modeled into *R-C* circuit with a LED. For the OLED drivers, rather than PMW program method and PMOLED driver design, AM program method and AMOLED driver design are more beneficial to OLED for better display quality, longer lifetime and bigger panel size.

However, the conventional AMOLED driver design is not suitable enough with voltage scaling design for its color distortion under scaled supply voltage. I design a new AMOLED DVS-friendly driver to overcome those unexpected problems. Simulations are made, proving its excellent reliability over the conventional ones.

3.0 FINE-GRAINED DYNAMIC VOLTAGE SCALING (FDVS)

In conventional OLED design, a static V_{dd} is selected to be high enough to supply the maximum I_{cell} to the whole display panel. The key idea of dynamic voltage scaling is to use the drivers dynamically regulate the supply voltage separately according to different display content. Although the luminance might be defected when the supply voltage is scaled, the maximum I_{cell} is seldom reached during the normal OLED operations because the maximum gray level is needed by only very few color compositions at their highest brightness. V_{dd} may be safely reduced with DVS-friendly OLED driver design under most of the operating conditions without incurring any color distortions. Hence, with the DVS-friendly driver circuits, there is more voltage scaling potential, and the display power can be reduces without incurring image quality degradations. In this section, a system of fine-grained dynamic voltage scaling (FDVS) method will be introduced from several aspects covering voltage scaling and image processing issues.

3.1 DISPLAY CONSTRAINS

To scale the voltage supply to the display panel, it is the most significant to figure out the mechanism of image display and color tuning, which might cause display perspective constrains. Also to evaluate the image quality, some image evaluation standard must be applied to guide the image processing.

3.1.1 Color Space

OLED display pixels colors can be quantitatively tuned by specific color spaces, which the abstract mathematical model to present color characters by of 3 or 4 basic visual components. Generally the color space that digital displays technologies adopt is based on RGB model.

The RGB color model is an additive color model in which red, green, and blue light is added together in various ways to reproduce a broad array of colors. The name of the model comes from the initials of the three additive primary colors, red, green, and blue [36], since human retina has three kinds of cells that sense the lights at short, middle, and long wavelengths, respectively. The colors in RGB model can be easily tuned to cover human's visual color perception. Some implementations use 16 bits per component for 48 bits total, resulting in 16.7 million colors distinct colors [37]. As presented before, RGB color space is widely used in OLED design. And an OLED pixel is composed with red, green and blue OLED cells.

In traditional display technology, the colors' luminance is affected by many issues. For example, in LCD technology, the final luminance people perceived is the product of both RGB tuned by liquid crystals and luminance intensity tuned by BLUs. The RGB control signals can't be directly reflexed from the display panels. On a typical standard LCD display, an input intensity RGB value of only outputs about 22% of full brightness of the BLUs [38]. However, when it comes to OLED display panels, lights are emitted directly from organic layer in a linear relationship with current, the RGB color tuning can be more efficiency and precise.

Constrains from the RGB space are focused on two aspects. First of all since the RGB is an additive color space, the proportion of each dimension should be balanced. This can be overcome by the biased OLED cell area in each pixel. Secondly, since only if the proportion of red, green and blue maintains the same the color will be the same and the luminance will change linearly

with the RGB space, the voltage supply should be scaled simultaneously for each dimension. Generally, different sub-pixels should share the same the power supplier.

3.1.2 Image Quality Criteria

When processing the image, the criteria of image quality will definitely be another important constrain concern. Image quality is a characteristic of an image that measures the perceived image degradation (typically, compared to an ideal or perfect image). Imaging systems may introduce some amounts of distortion or artifacts into the signal, so the quality assessment is an important problem.

There are lots of criteria for image quality evaluation, like sharpness, noise, color accuracy and distortion, so on and so forth. However, in the DVS process, the visual quality of the original image does not matter. What is more important is the distortion condition between the original image and the processed image after voltage scaling. To evaluate image distortion, there are many conventional standards like peak signal-to-noise ratio (PSNR) and mean squared error (MSE). However such standards only focused on the image data's mathematic differences rather than the human visual percept. If we strictly evaluate the image distortion in a mathematic perspective, some undetectable distortion introduced by the DVS might be counted, which constrains the DVS space and hence the power saving efficiency.

Nowadays, the criteria of image quality have been well investigated, combining the research on human visual system (HVS). The characters of HVS are widely applied into image processing studies. For example, when it is noticed that the color resolution perception of the HVS is much lower than image's actual resolution, the color information can be sampled into lower level and suitable brightness value. Another example is image compression, like JPEG. The HVS model

will omit those high frequency details, so JPEG format will be more condense without any perceptible loss of quality. When this concept is adopt into the image distortion evaluation. Some distortion that people cannot recognize can be ignored and provide the voltage scaling with more space [40].

With HVS study, one of the most popular image quality evaluation methods is structural similarity index (SSIM). It is a method for measuring the similarity between two images, based on human perceptual quality. In SSIM system, 1~0.98 means high quality or very less distortion, 0.98~0.96 means medium quality, 0.96~0.94 means low quality, and below 0.94 means unacceptable or severe distortion [40][41]. In this work, I use SSIM index to evaluate the image quality from dynamic voltage scaling. Figure 3.1 shows some examples for the linearly dimed images of different SSIM values.

(a) (b) (c)

Figure 3.1 Examples of Images Linearly Dimed to Different SSIM Values:
(a) SSIM=1 (Original Image); (b) SSIM=0.98; (c) SSIM=0.96

In these images, the pictures are linearly dimmed to specific levels. With SSIM of 0.98, the shadows in the image are darker and the colors are not as brilliant as the original. While with the SSIM of 0.96, the distortion becomes more obvious, even the high light spots in the image are tend to be grey. However, since the image is linearly dimmed, each pixel suffers the same distortion, and the relative display content is remained the same. With conventional quality standard, for example, mean square error (MSE), the distortion levels for red, green and blue

dimensions are 181.75, 141.07, 46.91 respectively for SSIM=0.98, and 340.0, 263.98, 87.84 respectively for SSIM=0.96. Obviously, compared to MSE extremely high and massive values the SSIM is much easier for image quality evaluation. I am using SSIM as the image quality evaluation criteria for voltage selecting and quality control. This algorithm is written with Java, which can offer high computation speed, and won't cause much power overhead to the whole system.

3.2 OLED POWER CALCULATION

The light emitting efficiency of OLED cells ($\eta=L/P$) is measured by the ratio between the cells luminance L and the power consumption $P=I\cdot V$. Here I and V are the current and the voltage through the OLED cells, respectively. Since the current is constrained by the luminance requirement from OLED cells, the power consumption is mainly determined supply voltage [42].

The luminance of an OLED cell is proportional to the magnitude of driving current while the displaying efficiency varies for different colors. However, different OLED products have different pixel area, luminance range, and resolution, size and power efficiency, which might introduce variance in the power evaluation. Hence in my evaluation, I referred the power model of a piece of 2.8" AMOLED QVGA display module with an integrated driver circuit, µOLED-32028-PMD3T, from 4D Systems [43] as shown in Figure 3.2. It can be seen that the power consumption of color blue is about 2 times that that of red and green. This result also fit the biased OLED pixel structure presented before.

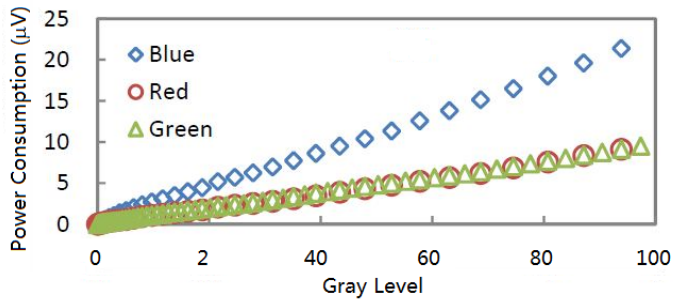


Figure 3.2 OLED Power Consumption Modeling Based on RGB Space [43]

The power consumption of a single color OLED cell is $P_{OLED} \approx I_{cel} \cdot V_{dd}$. For a color tunable OLED pixel with three basic color OLED cells, the total power consumption $P_{pixel} = P_{OLED}(R) + P_{OLED}(G) + P_{OLED}(B)$. Here $P_{OLED}(R)$, $P_{OLED}(G)$, $P_{OLED}(B)$ are the power summation of red, green and blue OLED cells respectively. It's remarkable that the variety of the display efficiency of the OLED cells for different colors have been taken into account in experiments. Since the efficiency is different from color to color, the power consumption in each RGB dimension will be simplified to ratio in this thesis. To achieve the same luminance, the ratio of the required power consumptions of red, green and blue OLED cells is about 1:1:2. And when the supply power, which is provided to the whole display panel, is scaled, it is assumed that all the color dimensions will linearly decrease in luminance. Also in the later experiment evaluation, the test results are not given by actual power value but the comparison ratio between the original image and processed image.

3.3 LOCAL VOLTAGE SCALING

The supply voltage is the most important factor to the power consumption. The most efficient way to explore the DVS potential is to manage each driver's supply voltage to adapt its display

content as much as possible. However, it will not be a good trade off to scale drivers pixel by pixel in the display panels. That will consume too much time and energy in image analysis and voltage regulating. A suitable trade-off might be to divide the display panel into multiple sections, covering specific amounts of pixels. And each display section will have its own voltage regulator to scale the supply voltage dynamically to specific image content. Using DVS-friendly drivers to dynamically scale supply voltages in display panel with multiply sections, is the basic concept of fine-grained dynamic voltage scaling (FDVS).

This concept has been adopted in LCDs' back light local dimming technique. With independent supply voltage and other control signals, the LCDs' back light can be locally dimmed to achieve power saving [45][46]. And lots of study and actual products have proved that this method is very efficient. Scientist doing multi-section based dimming, can raise the general power saving more than 55%, which is 12 times than global panel dimming [47]. Also relatively techniques have already applied to real TV products by LG and Samsung [48].

This idea can be applied into OLEDs definitely. On one hand, it is a good solution to reduce the power consumption by reducing the supply voltage, which is the main factor of power consuming in OLEDs. And on the other hand, it gives a solution to the limitation of size in present manufacture technique. A good example is that, Samsung and LG have recently produced prototype 55" OLED TV panels. These panels have already been unveiled in the FPD International 2011 exhibition in Japan. The prototype just gave a try in combining multiple OLED sections to form a big display panel [49]. And, since the DVS-friendly drivers can perform voltage scaling without obvious image distortion in a huge range, the DVS can be more aggressive.

In FDVS technique, an OLED panel is divided into multiple display areas, of which the V_{dd} is controlled independently. An object in image content is defined as a group of pixels with the similar RGB distribution. It can be noted that human visual system is more sensitive to the major objects in discontinuous areas. To achieve the maximum power saving while maintaining a high quality of human visual perception, the V_{dd}'s of each display area is mainly based on the RGB components of the parts of the major objects(s) in the area. For the display areas that do not include the major object(s) or the maximum luminance is not high, an aggressive V_{dd} scaling is applied to obtain the maximum power saving with the minimized impacts on the image's structural similarity.

When local voltage scaling is applied, the luminance can be simplified to step linear functions. When V_{dd} is reduced, the colors of the pixels with high luminance (which can also be presented by I_{cell}) are linearly reduced first, while lower ones maintain almost the same. $GL_{threshold}$ is the minimum gray level above which the I_{cell} will be reduced from the required magnitude at a scaled $V_{dd,}$ or it can be seen as the step node in the step linear function. GL_{MAX} is maximum gray level or 255 in RGB space. A parameter called "sacrificed luminance ratio (*S.R.*)" is proposed to denote the ratio between the total sacrificed luminance at the scaled V_{dd} and the total luminance of the whole OLED panel as:

$$S.R. = \int_{GL_{threshold}}^{GL_{MAX}} \left(\mathrm{R_i} + \mathrm{G_i} + \mathrm{B_i}\right) \Big/ \int_{0}^{GL_{MAX}} \left(\mathrm{R_i} + \mathrm{G_i} + \mathrm{B_i}\right) \tag{3.1}$$

The total scarified luminance is calculated as the integration of the luminance of the pixels in which at least one color OLED cell's gray level is beyond $GL_{threshold}$. The total luminance is the integration of the luminance of all pixels in the OLED panel. As shown in Figure 2.7 (b), the scaling of V_{dd} incurs the decrease in $GL_{threshold}$ and consequently, the increase of the total scarified luminance.

S.R. is used to heuristically guide the V_{dd} scaling in the FDVS technique. For example, I found that when *S.R.* = 0.12, the corresponding V_{dd} can achieve a SSIM close to 0.98, which is the lower bound of a high-quality image. When the FDVS is applied the first scaled voltage will be given based on the *S.R.* ratio. Then additional voltage will be adjusted based on SSIM.

Since each image is composed by three dimensions. I create the image matrix of a color image as: MSSIM = [R:G:B], where R, G, B are the matrices of the luminance of the red, green and blue OLED cells of the OLED panel. The SSIM of the new image at the scaled V_{dd} with regard to the original image at the normal V_{dd} can be calculated as:

$$SSIM = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)} \tag{3.2}$$

Here μ_x and μ_y are the average of the image matrices of the new image and the original image, respectively; σ_x and σ_y are the variances of each image matrices, respectively; σ_{xy} is covariance. C_1 and C_2 equal 2.55 and 7.56 for RGB color space, respectively.

3.4 IMAGE COMPENSATION

In the OLED display panels, no matter what driver circuit is used in voltage scaling, there will be inevitable image distortion. More concretely, the pixels in the OLED display panels will be reduced with the same gray levels when voltage scaling is applied. However, some tricks about image compensation or color remapping will help to compensate the image distortion and create even bigger voltage scaling space for power saving.

Since the OLED cells' luminance is determined by the programing signals, the programing signal can be used to compensate the luminance when the voltage scaling is applied. This

mechanism can be implemented by different ways. The display content in the display RAMs can be reprogramed by system control, or some look up table devices can be built in the peripheral driver circuits to remap the original signals to new ones. Hence when the control signals are exported to drivers, the signals have already been amplified or remapped to raise the OLED cells luminance against distortion [50]. However, in this thesis, since the peripheral circuit or higher level control is not covered, the color compensations are implemented in image processing directly. And the power of this mechanism is not considered into the whole power consumption.

As presented before, the DVS-friendly driver's color distortion under voltage scaling can be simplified to step linear functions. First of all, within high gray level range ($GL_{threshold} \sim GL_{MAX}$), the luminance is linearly reduced by α, and $GL_{MAX}' = GL_{MAX} \cdot \alpha$. Secondly, except those pixels, whose luminance are beyond the GL_{MAX}', the distorted pixels' luminance can be compensated with amplified the control signal by α. With low gray level range ($0 \sim GL_{threshold}$), the distortion of the pixels can be ignored. Also for those pixels whose luminance cannot be compensated, the control signal should be raised to maximum GL_{MAX} to achieve least distortion.

3.5 FDVS SOFTWARE FLOW

In the following image processing simulation, a set of program is written to perform the FDVS software flow designed in this thesis. To summarize the general function of FDVS methods, the software flow can be seen in Figure 3.3.

Step 1: OLED cells characterization. As shown in Figure 2.7 (a) and (b), the relationship between the $GL_{threshold}$'s of color OLED cells and the V_{dd} scaling is characterized as stored as a look up table.

Step 2: Image partitioning. The image is partitioned into multiple display areas based on the OLED panel size, resolution and the voltage regulator locations. The V_{dd}'s of each area are controlled separately.

Step 3: V_{dd} selection. A *S.R.* is applied to select the $GL_{threshold}$ and consequently, the V_{dd} of every display areas based on Eq. 3.1 and the OLED cell characterization table obtained in Step 1.

Step 4: Color remapping. Color remapping is applied to improve the image quality if it cannot reach the requirement (e.g., SSIM) after step 3.

Step 5: Evaluation: If the image quality still cannot meet the requirement after step 4, we increase V_{dd}'s and repeat step 3 and 4. Otherwise, the flow ends.

Fig. 3.3 summarizes overall flow of FDVS technique.

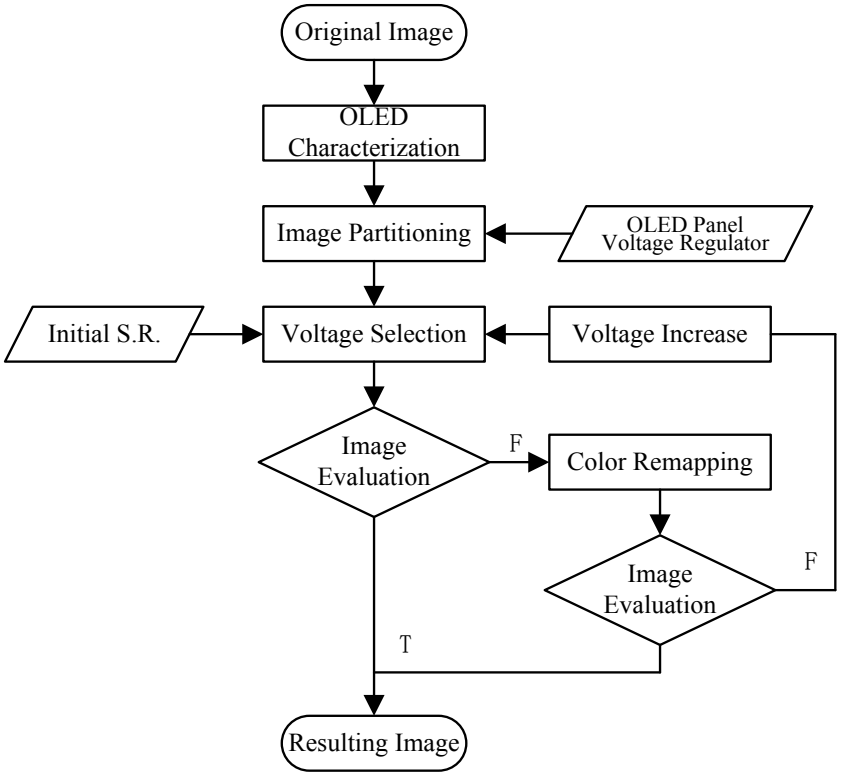


Figure 3.3 Overall Flow of FDVS Technique

3.6 CONCLUSION

In this section, the technique details are illustrated about the fine-grained voltage scaling (FDVS). Concerning constrains from RGB color space and SSIM evaluation standard, the FDVS method is designed. In FDVS system, the display panel will be built with DVS-friendly drivers and divided into multiple sections. In each section, aggressive voltage scaling will be performed according to display content while maintain image quality high enough. Color compensation mechanism is applied into the FDVS method, which will compensate the inevitable distortion during the dynamic voltage scaling. A software flow is design to perform the FDVS method, which will be the basic tool in following simulation evaluations.

4.0 FINE-GRAINED DYNAMIC VOLTAGE SCALING (FDVS)

In this section, the effectiveness of the FDVS technique is tested from several aspects based on some classic image processing samples, i.e., 'Lena' and 'F16', as shown in Figure 4.1. The resolutions of these classic figures are chosen to be 500×500. Also the RGB diagram is presented below. It presents the distribution of the RGB grey levels. It is remarkable that 'Lena' has well-balanced color profile, texture and contrast ratio, while the color profile of 'F16' is heavily skewed to bright colors, which corresponds to the high gray level region of the OLED cells. The color profiles of 'Lena' and 'F16' are also shown in Figure 4.1.

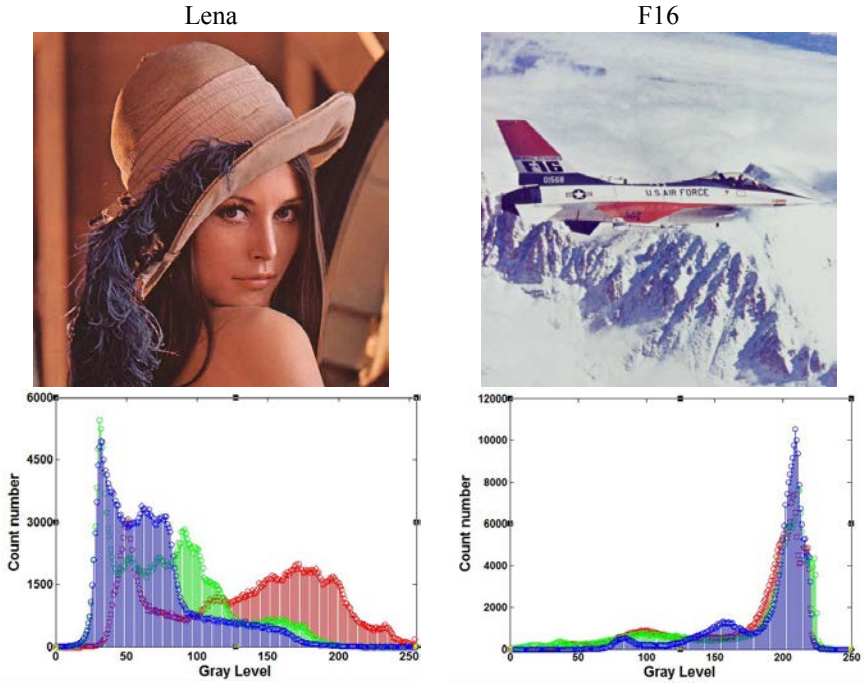


Figure 4.1 Original Image Samples and Their RGB Profiles

4.1 EFFECTIVENESS OF DVS-FRIENDLY DRIVER DESIGN

As discussed before, DVS-friendly OLED driver can maintain the color accuracy as long as the required I_{cell} below the maximum driving strength of T_4 at the scaled V_{dd}. Figure 4.2 shows the displayed images on the OLED panels with conventional drivers and DVS-friendly drivers, respectively, at a scaled V_{dd}=11.2V. The corresponding SSIMs are also shown below the images.

SSIM=0.9209 SSIM=0.9863

(a) (b)

Figure 4.2 Image Quality Comparison of 'Lena' for Different OLED Driver Designs: (a) Conventional Driver; (b) DVS-friendly Driver

Significant image quality degradation is observed in Figure 4.2 (a) due to the V_{dd} scaling induced color distortions and luminance reductions. The SSIM of Figure 5.2 (a) is 0.9209, which is far below 0.94 and categorizes the image quality into "unacceptable" range. As a comparison, the SSIM of my design is 0.9863, which is categorized as "high quality" range. Compared to the conventional OLED panel working at the normal V_{dd} of 15V, the power saving of Figure 4.2 (b) is 27.41%. To achieve a SSIM=0.98 in the conventional OLED driver design, the V_{dd} must be increased to 14V, of which the power saving is only 20.66% (it is not shown in Figure 4.2).

Figure 4.3 shows the SSIM values of 'Lena' at different V_{dd}'s for both conventional and DVS-friendly OLED driver designs. The image quality of conventional designs quickly degrades when V_{dd} decreases while that of DVS-friendly designs keeps "high quality" (SSIM>0.98) until V_{dd}=11.2V. In this comparison, neither color compensation nor FDVS is applied.

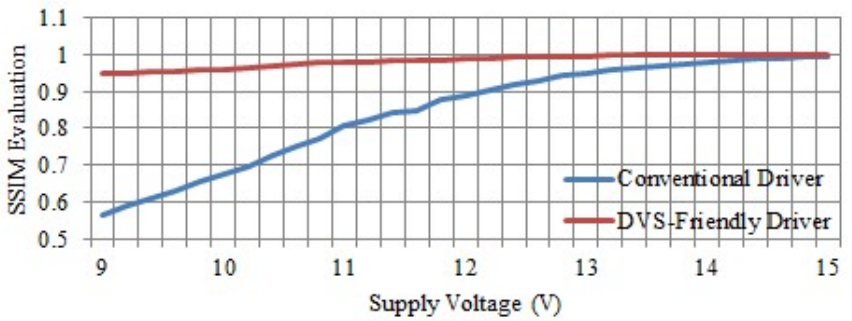


Figure 4.3 Supply Voltage Comparisons of Two OLED Driver Designs at Different SSIM Indexes

The image comparison of 'F16' with different OLED driver designs for SSIM=0.98 is shown in Figure 4.4 The required V_{dd}'s are all higher than those of 'Lena' and result in lower power saving's. It can be explained as the follows:

V_{dd} = 14.0V
Power saving = 20.23%
(a)

V_{dd} = 13.2V
Power saving = 22.57%
(b)

Figure 4.4 Images of 'F16' of Different OLED Driver Designs at Different V_{dd}'s for SSIM=0.98: (a) Conventional drivers; (b) DVS-friendly drivers

As shown in the color profiles of Figure 4.4, the red color of the OLED pixels in 'Lena' spreads over the whole gray level range while the other colors is mainly in the low luminance region. However, in 'F16', all color OLED cells are mainly located at high gray level region. As discussed before, the DVS-friendly driver designs are more effective in maintaining color accuracy at low gray level region than high gray level region. Therefore, the V_{dd} of 'Lena' can be scaled more aggressively than that of 'F16' since less color distortions will be incurred to the color OLED cells working at low gray level region.

4.2 EFFECTIVENESS OF COLOR COMPENSATION

We also evaluated the cost of color remapping technique to improve the image quality of both conventional and DVS-friendly OLED driver designs. The cost is measured by the ratio between the numbers of the pixels to which the color remapping is applied and the total pixels.

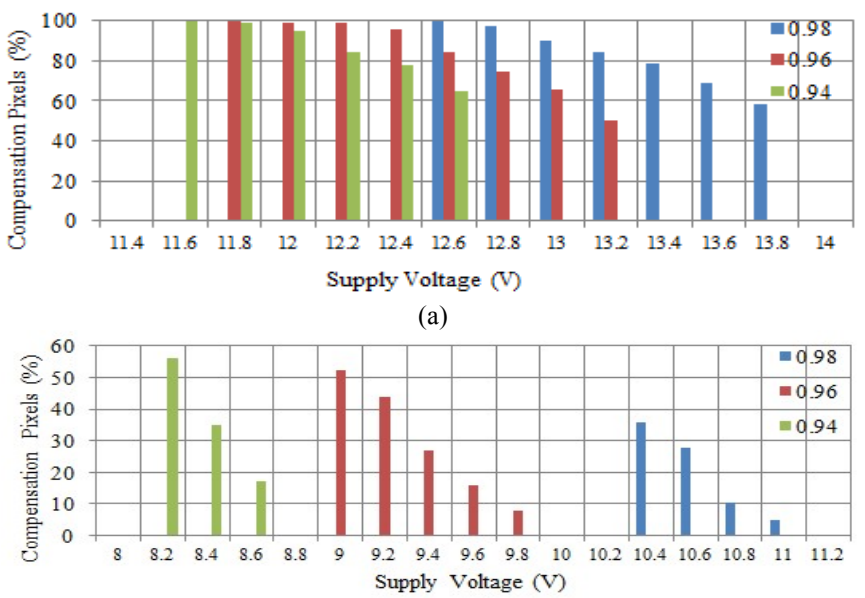


Figure 4.5 Color Remapping Costs of 'Lena' with Two OLED Driver Designs at Different V_{dd}'s for SSIM=0.98, 0.96 and 0.94: (a) Conventional Drivers; (b) DVS-friendly Drivers.

Figure 4.5 shows the color remapping costs of 'Lena' with two OLED driver designs at different V_{dd}'s for SSIM=0.98, 0.96 and 0.94, respectively. V_{dd} is safely reduced to 11.2V in DVS-friendly driver designs for a SSIM of 0.98 without any color remapping while V_{dd}=14V is required in conventional driver design. Continue reducing the V_{dd} incurs the increase of color remapping cost. If V_{dd} is scaled down to 12.6V in conventional driver designs, the colors of all OLED pixels (cost=100%) must be remapped for SSIM=0.98; Further reducing the V_{dd} below 12.6V cannot guarantee SSIM=0.98 even color remapping is applied. In DVS-friendly driver designs, however, a SSIM of 0.98 can be achieved even at V_{dd}=10.4V with a color remapping cost of merely 35.92%.

Figure 4.6 shows the examples of the compensated images of both OLED driver designs at the same color remapping cost=24.06% under V_{dd}=12V. The SSIMs of DVS-friendly drivers and conventional drivers are compensated to 0.9924 and 0.9032 respectively. Here 24.06% is the ratio between the number of all pixels whose colors are distorted at V_{dd}=12V and the total pixels in 'Lena'.

SSIM = 0.9032 (a) *SSIM* = 0.9924 (b)

Figure 4.6 Image Comparisons at the Same Color Remapping Costs and V_{dd}=12V: (a) Conventional Drivers; (b) DVS-friendly Drivers

4.3 EFFECTIVENESS OF COLOR FDVS

In the global DVS scheme in [24], increasing V_{dd} reduces the number of pixels that cannot be fully compensated by paying the degradation of power efficiency. FDVS, however, allows V_{dd} adjustment at a smaller granularity and improves the power consumption of OLED panel and image quality.

Figure 4.7 shows images of 'Lena' and 'F16' at SSIM=0.98 after FDVS is applied. The DVS-friendly driver design is adopted. Images are divided into 16 display sections, whose V_{dd}'s are adjusted separately and no color remapping is applied. The V_{dd} maps of every display areas

are also shown besides the images. Each value in the voltage map indicates the supply voltage to that section.

As shown in Figure 4.7 (a), the OLED power saving of 'Lena' is raised by 43.1% (from 27.41% to 39.24%), compared to the global DVS scheme with DVS-friendly driver designs. In 'F16', the power saving is raised by 25.9% (from 22.57% to 28.44%). The lower absolute power saving is because the major color occupies most of area in 'F16'. Small V_{dd} adjustment spaces are left to each display areas, as shown in the V_{dd} map of Figure 4.7 (b). Human visual perception, however, is mainly affected by the major color's brightness.

9	10.2	10.8	10.2
10.2	10	10.6	10.4
11	10.2	10.4	9.6
11.2	9.4	11.6	11.8

V_{dd} Map (V) Power Saving = 39.24%

(a)

12.2	12	12.2	12.4
12.4	12.4	12.6	12.6
12.2	10.8	11.8	12.6
12.4	12	12.2	12.6

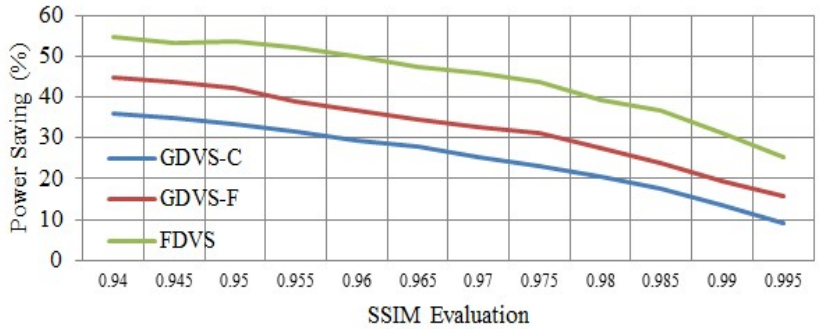
V_{dd} Map (V) Power Saving = 28.44%

(b)

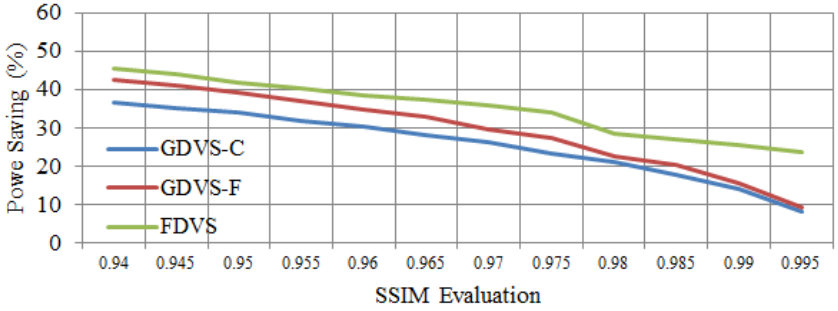
Figure 4.7 Power Saving Evaluation of FDVS in Different Images for SSIM=0.98:
(a) 'Lena'; (b) 'F16'

Figure 4.8 summarized the power saving and the image quality of different technique combinations, including conventional OLED driver design with global DVS ('GDVS-C'), DVS-friendly driver design with global DVS ('GDVS-F'), and DVS-friendly driver design with fine-

grained DVS ('FDVS'). Here we did not evaluate the effects of color remapping because it heavily relies on the specific software and hardware designs and does not directly accounts for the total OLED power consumption. Substantial power saving is obtained by the DVS-friendly OLED driver designs and FDVS technique compared to the global DVS technique with conventional driver designs.



(a)



(b)

Figure 4.8 Effectiveness of Different Techniques Summary: (a) 'Lena'; (b) 'F16'

4.4 CONCLUSION

In the section, lots of image processing based simulations are performed to thoroughly evaluate the FDVS's performance. Experimental results are made based on two classical real images. The effectiveness of FDVS is proved in several aspects of DVS-drivers, color compensation and general performance to other possible power saving methods. Compared to global voltage

scaling with conventional drivers or DVS-friendly drivers, the FDVS systems can achiever 25.9% ~ 43.1% more power saving for the same image quality with significantly reduced color remapping costs.

5.0 CONCLUSION AND FUTURE WORK

In recent years, OLED have emerged as new display techniques for mobile multimedia devices. Compared to existing technologies such as LCD, OLEDs are thinner, brighter, lighter, and cheaper. However, the OLED panel display is still the biggest contributor to the total power consumption of a mobile device.

In this thesis, A DVS-friendly OLED driver design is also proposed to enhance the color accuracy of the OLED pixels. Compared to conventional OLED drivers' performance, only pixels in high luminance range will suffer linear distortion when the supply voltage scaled. Also a set of dynamic scaling method is proposed as fine-grained dynamic voltage scaling (FDVS) technique, to reduce the OLED power consumption. In FDVS system, with DVS-friendly drivers, an OLED panel is partitioned into multiple display sections, of which the supply voltage is adaptively adjusted based on the displayed content. And color compensation will be applied during voltage scaling.

My experimental results show that compared to the existing global DVS technique, the FDVS technique can achieve 25.9% ~ 43.1% more OLED power saving while maintaining a high image quality measured by Structural Similarity index (SSIM=0.98). Further analysis shows FDVS technology can also effectively reduce the color remapping cost when color compensation is required to improve the image quality of an OLED panel working at a scaled supply voltage.

The future work is mainly focused on extending this method to real time analysis. Since the present work introduced in this thesis is based on static single frame, which is used to exam the advantage of the drivers and scaling method, the real time character s are not discussed. Some constrains from the voltage regulators, OLED refreshing speed and real time image analysis will be discussed in the future work.

Also some technique details will be modified. The circuit simulation in this work is based on 130nm CMOS technology. However, as thin film transistor (TFT) technology is the main driver materials, there is still some performance different from the simulation to real product design. Hence more detailed circuit study will be implemented with more precise models. Also the power consumption in this thesis didn't account for the peripheral power consumption like image processing and voltage regulating. Hopefully, this FDVS can be implemented in real embedded systems like mobile phones or tablets. At that time a higher level view of power consumption can be made.

Since the power optimization study on OLED is still in the start stage, I hope this thesis can contribute some to this study area. Also I will continue studies in this area in my Ph.D. stage. I will put much more effort to this work in the future.

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