Chapter 1

Introduction

1.1 Overview of the Organic Light Emitting Diode (OLED) Displays

Flat panel display (FPD) technologies have been researched and developed extensively nowadays including liquid crystal displays (LCDs), plasma displays (PDPs), field emission displays (FEDs) and organic light emitting diodes (OLEDs). Although LCDs are the most popular products, there are still some critical problems need to be solved such as response time, the range of the operation temperature, etc. Recently, with the rapid progress in the device properties of organic light emitting diode (OLED) such as luminescent efficiency [1.1], brightness, and life time [1.2], OLED displays have been viewed as one of the most promising research topic to replace LCDs for the next generation of flat panel display (FPD) due to their various excellent features including wide viewing angle (>160 degrees), fast response time (~μsec) which can show fast moving images, high contrast ratio, high brightness, low operation voltage, low cost, and possibility to be made on the flexible substrate [1.3]-[1.5]. Unlike LCDs, OLED displays have the self-emissive characteristic, so they do not require any backlight, diffuser, polarizer film, and so on. Therefore, OLEDs possess simple structure with compact module. Besides these superior features in terms of display performance, all solid state nature of OLED device is the essential factor as the next generation flat panel display, because it could offer us tremendous potential for system integration.

The development history of organic light emitting diode (OLED) began in 1963; Pope et al. applied an electronic voltage on the single crystal of about 20mm thickness to observe its electroluminescence effect [1.6]. However, the operation voltage was too high (>100V) to be used in the commercial application. In an attempt to reduce the bias voltage, Vincett et al. used thin organic film of similar materials in their device [1.7]. Although the operation voltage was lowered below 30V, the quantum efficiency was only about 0.05%, presumably owing to the inefficiency of electron injection and the inferior quality of the evaporated anthracene films. It was until 1987, a significant breakthrough in organic electroluminescent devices was made by Tang and Van Slyke at Eastman Kodak Company [1.8]. They announced the bi-layer organic thin film device structure with one layer capable of only monopolar transport and developed low molecular weight organic materials of aluminum (III) tris(8-hydroxyquinoline) (Alq_3) as the light emitting layer. By using this hetero-layer structure, each a few ten nanometers thick prepared by vacuum vapor deposition, sandwiched between indium tin oxide (ITO) and Mg:Ag alloy electrodes (Mg0.9Ag0.1), they could achieve high external quantum efficiency (1%photon/electron), luminous efficiency (1.5 lm/W), and brightness (>1000cd/m^2) at low bias voltage below 10V. In addition to the small molecular based electroluminescent devices, in 1990, Burroughes at Cambridge University first reported a polymer based organic device using PPV (p-phenylene vinylene), fabricated by spin coating, as the light emitting material between ITO and Al [1.9]. Since then, many companies around the world started to study and invest this promising OLED technology. Among them, Japanese companies focus on small molecular organic light emitting diodes (OLEDs), meanwhile European and American Inc. are involved in polymer based light emitting diodes (PLEDs).

The basic structure of OLED is so called sandwich structure, which is composed of an emitting layer between electrodes. Besides the conventional bi-layer structure mentioned above, there are also single-layer and triple-layer structures [1.10]-[1.11]. Although four- or even five-layer structure was constructed and fabricated successfully for realizing longer lifetime, a simple structure is more practical with easy manufacturing process.

1.2 Display Architecture for OLED

OLEDs can be classified into passive matrix OLED (PMOLED) and active matrix OLED (AMOLED). Nowadays, some have already been introduced in products [1.12]-[1.14]. The panel applications include small-size portable monochromatic, multi-color, and full-color displays such as car stereos, mobile phones, camcorders, personal digital assistants (PDAs), and digital still cameras (DSCs) where the earliest commercial PMOLED is a multi-color automotive radio console, fabricated on glass substrate with 256 × 64 pixels in 1999 [1.15], and the first full-color AMOLED, 2.2 inch of the panel size, is applied on DSC in 2003 [1.14].

1.2.1 Passive Matrix OLED (PMOLED)

Passive matrix OLED array is a very simple structure that the whole panel consists of a matrix of transparent anodes, as the data electrodes, on which a thin layer emissive OLED is spun, followed by the structured metal cathodes, which forms the rows. The cross section between anode and cathode is the emitting area for OLED while specific current flows through it. Because thin film transistors (TFTs) are not used in pixels, easy structure, facile fabrication process, low cost, and high yield rate can thus achieved. Besides, aperture ratio can also be improved substantially. Passive matrix scheme needs additional ICs outside the panel to drive it. When a specific row line is selected during one scan time, every signal line, namely the column line, supplies the corresponding current to light every diode. Therefore, every OLED is biased in a pulsed operation and the time available for organic diode to illuminate is very short. The peak brightness is proportional to the number of row lines. For example, there are 100 row lines, peak brightness 10000cd/m^2 is necessary to achieve average brightness of 100cd/m^2 in the panel. Although many of the passive matrix OLED displays have already proven their abilities with improved design and performance such as longer lifetime, and lower power consumption, [1.16]-[1.18], there are still several problems as listed below, which limit their range of application to the low-end products, where the number of rows is around few hundred.

- **High current and high voltage drops in each row/column that would dissipate more power.**
- **High instantaneous luminance of each pixel that would degrade OLED device rapidly in respect to lifetime and emitting efficiency.**
- **Large OLED capacitance and resistance that restrict display luminance, format, and image quality**
- **Susceptibility of cross talk.**

In order to overcome these problems, active matrix type is developed for high image content and high resolution applications in the future. The goal of active matrix OLED (AMOLED) is to generate a current source corresponding to data voltage at each pixel which can eliminate high current encountered in the passive matrix approach. In addition, active matrix displays could have lower power consumption than PMOLED, omit requirement for cathode pattering, and reduce extra interconnect with integrated driver electronics.

1.2.2 Active Matrix OLED (AMOLED)

Although active matrix displays are expensive with complex structures, they have high image contrast, better display performance and are necessary for high level and large panel size displays. In the active matrix display, OLED is integrated with thin film transistors (TFTs) in a suitable manner. The simplest structure is a single transistor series with OLED [1.19] that the TFT can supply specific current for OLED when this pixel is selected. This approach has higher yield than any other design containing more than one transistor in each pixel. Although it allows much lower current levels compared with passive matrix driving, it has no capability of memorizing data voltage. For OLED, at least two transistors and one capacitor are needed in each pixel in order to illuminate continuously throughout the frame [1.20]-[1.21]. The first TFT is used as addressing switch (switching TFT) to transmit data voltage to the gate voltage of another TFT when the scan line is selected, and the second TFT (driving TFT), which functions as a controlled current source, converts this data voltage into specific current for OLED. By means of the existence of storage capacitor, driving TFT can supply constant current to OLED, even when the scan line is deselected. It reduces drive current and thus improves the lifetime of OLED device. The brightness of one pixel, which is proportional to diode current from power supply line passing through driving TFT, can be modulated by varying data voltage and updated every frame time. This driving method is so called conductance control gray scale (CCG) [1.22]. The peak brightness is exactly the average brightness across the panel. It is desired for driving TFT to be biased in the saturation region with the easier analytical calculation, because the drain current of this driving TFT is determined only by gate to source voltage regardless of the drain to source voltage. However, from the square equation for the transistor current, it is obvious that any variations of electrical characteristics of a transistor such as threshold voltage, mobility and, subthreshold swing variation due to process variation will result in great variation of the output driving current. This becomes a crucial problem when large panel size and high resolution displays are developed in the future. As for the lifetime of AMOLED, it is mainly attributed to the compound effect of the degradation of OLED device and the decay of TFT current and many efforts were made to overcome OLED threshold voltage variation by using improved materials and innovative structures.

1.3 Driving Schemes for AMOLED

1.3.1 Comparison between Active Matrix Liquid Crystal Display (AMLCD) and Active Matrix Organic Light Emitting Diode (AMOLED)

Based on different driving manners, it can be divided roughly into two modes, that is, voltage driven and current driven. Twisted nematic liquid crystal displays (TN-LCD), super-twisted nematic LCD (STN-LCD), and thin film transistor LCD (TFT-LCD) belong to voltage driven displays. Liquid crystal displays (LCD), as implied by the name, utilize optic characteristic of liquid crystal (LC) to display images. For TFT-LCD, the pixel consists simply of a single transistor and a storage capacitor. When the active element, which functions as a switch, is turned on, the driving voltage is written onto the pixel. Even when the transistor is off, each pixel retains the data voltage due to the storage capacitor. Applied drive voltage would determine the tilt angle of LC. Combined with the cold florescent tube, characteristics of the polarizer, and a proper distance between glass substrates at the same time, different brightness of light can be obtained. Because the TFT is used only as a switch, its uniformity for display performance is not as critical as employed as driving device for

AMOLED.

Attributed to the nature of emitting principle and physics mechanism, unlike LCD, OLED is a current driven device where luminescent behavior can be achieved while external current passes through a thin light emitting material. This specific current also determines emission characteristic and efficiency of OLED. For AMOLED, two transistors and one capacitor is needed for better performance in each pixel as mentioned in 1.2.2. In the conventional bi-layer organic structure, one layer is for the hole to transport and the other layer is for the electron to transport and emitting. When a positive bias is applied, the holes are injected into the highest occupied molecular orbit (HOMO, similar to valance band in the semiconductor) of the hole-transport layer, meanwhile the electrons are injected into the lowest unoccupied molecular orbit (LUMO, similar to conduction band in the semiconductor) of the electron transport layer. Due to the potential difference across OLED, both carriers move to emitting layer and combine to become excitons. These excitons appear unstable and would go back to ground state by releasing excess energy as light. Different wavelengths of the light can be obtained by vary dopants species used in the organic light emitting layer.

1.3.2 Amorphous Silicon Thin Film Transistors (A-Si TFTs) versus Low-Temperature Polycrystalline Silicon Thin Film Transistors (LTPS TFTs)

There are many candidates for driving OLED, i.e., single crystal silicon MOSFET, amorphous silicon TFT (a-Si TFT), polycrystalline silicon TFT (poly-Si TFT), and organic TFT (OTFT), etc. Although OTFT can be fabricated on the flexible plastic substrate, this technology is not mature yet [1.23]. Poly-Si TFTs can be divided into two types according to the process temperature, which are high-temperature polycrystalline silicon TFT (HTPS TFT) and low-temperature polycrystalline silicon TFT (LTPS TFT) and LTPS TFT is more attractive due to the low process temperature. AMOLED displays can also be built by integrating either a-Si TFT or LTPS TFT with organic light emitting diode. The difference between these two kinds of transistors mainly lies in fabrication process steps, structure, intrinsic characteristic, and performance including driving capability and stability [1.24]-[1.26].

Process Steps and Structure

Less process steps, usually five or even four mask process, are needed for the fabrication of a-Si TFT. They are gate electrode, a-Si/n$^+$ a-Si channel layer, source/drain electrode, passivation layer, and transparent ITO which result in bottom structure and the process temperature is below 350°C. Compared with a-Si TFT, LTPS TFT with top gate structure involves more process steps, nine to ten mask process are necessary. These include active poly-Si layer, implantation (N$^+$, N$^-$, P$^+$), gate electrode, interlayer dielectric, source/drain electrode, passivation layer, and ITO. Besides these steps, some extra equipments are required including

- Excimer laser annealing for crystallization of the a-Si thin films.
- Ion implanter or ion shower for ion doping to form the source/drain.
- Rapid thermal annealing or excimer laser annealing for activation of the dopants.

As a result, LTPS TFT sustains higher equipment cost than a-Si TFT.

Driving Capability

Due to the higher parasitic capacitors of gate/source and gate/drain overlaps resulted from unself-aligned structure and the nature of hydrogenated amorphous silicon, mobility of a-Si TFTs is generally below 1.0 cm^2/V-s which restricts its driving ability. In order to achieve specified driving current, the dimension must be enlarged but the aperture ratio would be reduced. Therefore, a-Si TFTs are usually used as switching device. With this intrinsic property, only n-type TFT is available when a-Si TFT is employed which in turn greatly reduces the flexibility of TFT and causes some undesired design difficulties. On the contrary, LTPS TFT possesses an electron mobility that is one or two orders of magnitude higher than a-Si TFT. This means LTPS TFT can provide enough current for every pixel and makes it a good candidate for the fabrication of small panel size and high resolution definition displays. For display applications, many advantages can be acquired by using high mobility LTPS TFTs such as the smaller dimension, resulting in higher aperture ratio and higher brightness, lower parasitic gate-line capacitance for improved display performance, and lower operation voltage so that lower power can be achieved. Because both n-type TFT and p-type TFT can be employed in the circuit with high driving capability, CMOS drivers can be integrated on the substrate.

Stability

The stability of TFT, meaning stable constant current source for OLED under long-term stress, is a crucial factor for AMOLED commercialization. The decrease of the current from driving TFT with circuit aging is due to the characteristic shift (ΔV_{th}) over time and this problem of brightness degradation appears in a-Si TFT [1.27]-[1.28]. When both gate and drain bias voltages are applied to an a-Si:H TFT, the ΔV_{th} depends strongly on the gate bias stress, but very weakly on the drain bias stress. Two mechanisms which include charge trapping in the gate oxide and the creation of defect states in the channel are commonly acceptable for explaining this phenomenon [1.29]. On the other hand, poly-Si

TFT is quite stable after long time bias and processes higher thermal endurance.

With recent progress in luminance efficiency of OLEDs and other technology [1.30], hydrogenated amorphous silicon (a-Si:H) TFT is sometimes preferred because of the well-established manufacturing technology developed for active matrix liquid crystal displays (AMLCDs) so that the better uniformity across the wafer compared with poly-Si TFT and the easier fabrication process of the large size TFT array on the glass substrate can be obtained. Although some promising results published recently have proven their feasibility and provided alternative solutions for AMOLED to commercialize [1.31]-[1.32], poly-Si TFT is commonly accepted and utilized to realize AMOLED development due to its better driving ability and stability than a-Si TFT. These features of poly-Si TFT not only makes it a good choice for switching and driving elements in the pixel, while OLED is a current driven device and sufficient current supply from TFT is essential for panel operation, but also enables the integration of row and column drive circuitry on the same panel to achieve possibility of completely system on panel (SOP). Integrated drivers have the potential for reducing driver IC cost and eliminating process steps like printed circuit boards and the TAB connectors and in consequence a number of innovative new displays with high performance in panel reliability and yield can be generated. Therefore, LTPS TFT is considered more suitable for the use of flat panel display because it can be fabricated on glass substrate while maintaining good properties.

1.3.3 Complementary Transistors: N-Type TFT and P-Type TFT

In the case of LTPS TFT, both n type TFT and p type TFT are available. Owing to the nature of free carriers, mobility of n-type TFT is usually higher than that of p-type TFT [1.22]. Besides, n-type TFTs can also effectively improve the dark gray level, increase contrast ratio, and decrease power dissipation of the display. Regarding the reliability of LTPS TFT, n-channel TFT has been greatly improved by introducing lightly doped drain (LDD) structure while p-channel TFT has inherent a good performance. Therefore, one additional mask and higher cost are needed for the fabrication of n-type TFT in comparison with p-type TFT. As for the circuit configuration, OLED is arranged at the drain end of p-type driving TFT in the circuit and gate to source voltage (V_{gs}) is determined by data signal voltage (V_{data}) and power supply voltage (V_{dd}), while V_{gs} of the circuit employing n-type TFTs that OLED device can only be arranged at the source end of driving TFT is ($V_{data} - V_{OLED}$). Owing to OLED degrades after a long operation period, in other words, the operation voltage (V_{th}) of OLED device often increases with time [1.33], V_{gs} would be changed, and constant current configuration is difficult to realize for conventional n-type TFTs circuit. On the other hand, when p-type TFT is used for driving OLED, the degradation of power supply voltage becomes a critical problem as the panel size and brightness grow up. As a result, threshold voltage degradation of OLED must be considered in the n-type TFTs circuit while the degradation of supply voltage must be solved in the p-type TFTs circuit.

1.4 Emission Structures for AMOLED

According to the electrode structure of the electroluminescent device, emission structures for AMOLED can be categorized to bottom emission, top emission, and top and bottom emission.

1.4.1 Bottom Emission Structure

The bottom emission AMOLED uses the transparent anode (ITO) connecting with driving device on the substrate, followed by electroluminescent layer and the reflective cathode (metal) on the top in order to increase light efficiency and device stability [1.34]. The emitting light which originally travels in all direction would passes through the transparent ITO and glass substrate. Because a color pixel consists of TFTs area, metal lines, and OLED emitting area, the larger of the TFT dimension and the more transistors occupying the substrate will inevitably result in the smaller OLED emission area, which mean lower aperture ratio. When the same brightness is required, it will lead to higher power consumption and deterioration of OLED device in bottom emission structure while applied in the high resolution and high brightness AMOLED [1.35].

1.4.2 Top Emission Structure

In the top emission structure, the reflective anode and semitransparent cathode are employed as electrodes. The reflective anode needs high reflectivity and suitable work function to maximize the light efficiency. In addition, it must provide adequate electric conductivity to achieve device reliability. OLED emits light to the opposite side of the substrate component. Therefore, high aperture ratio can be achieved regardless of the number of transistors and the dimension of TFTs on the glass substrate, that is, only few obstructions block light even when the pixels are fine or structured by complex array of multiple transistors and capacitors. This kind of emission structure is suitable for various complicated pixel designs, a-Si TFT backplane and high resolution displays with high efficiency and high reliability. From another point of view, top emission AMOLED can regulate the color coordinate to achieve larger color gamut by utilizing the light interference while the color reproducibility in the bottom emission OLED is chiefly determined by the intrinsic characteristic of emitting materials for red, green, and blue [1.36]-[1.37].

1.4.3 Top and Bottom Emission (Transparent) Structure

For top and bottom (transparent) AMOLED, in attempt to emit the light to the topside and bottom, both transparent anode and semitransparent cathode are utilized. It shows some transparency on the off state. The contrast ratio can be enhanced because of the non-reflecting semitransparent cathode with respect to the conventional structure. Transparent structure could offer display thin and light and makes it much easier to view displays in bright sunlight. However, the both side emission AMOLED needs the higher brightness than bottom emission one to compensate for the loss of the reflective light [1.38].

1.5 Processes in the Fabrication of AMOLED

The process for fabrication of AMOLED includes two main stages on the same glass substrate, that is, LTPS TFT technology (the backplane fabrication) and the OLED technology [1.39]-[1.40]. Processes for the conventional bottom emitting structure are discussed in this section.

Fabrication Process of LTPS TFT

In the LTPS TFT technology, the silicon films are first deposited in the amorphous phase at a temperature below 600°C and crystallized to poly-Si phase by excimer laser crystallization (ELC) which usually appears to be the most promising at the moment. After patterning of poly-Si layer, the active island region is formed. Gate oxide and gate metal are deposited sequentially and then patterned to form gate electrode. The region of source and drain are doped with impurity elements that are either phosphorous dopant for n-type junctions in n-channel TFT or boron dopant for p-type junctions in p-channel TFT. For transistor to work effectively, the dopant has to be activated to achieve low resistance for the source and drain contacts, that is, to achieve low sheet resistance in the source and drain regions. After TFT formation, an interlayer dielectric layer (ILD) is deposited to cover the whole region of the island and gate to prevent shorts between gate and data lines. The contact holes are then opened and data metal is deposited and patterned to form source and drain electrodes. After that, the passivation layer is deposited and opened for the fabrication of ITO electrode so that ITO could connect with the source of TFT while n-channel device is utilized for driving OLED. It is important that this passivation layer must provide protection of the metals from future etching in addition to a well-planarized surface for ITO deposition, because any roughness surface for ITO electrode fabrication would result in leakage current path and non-uniform current flow through OLED material. ITO electrode is then patterned and an adhesive SiO_2 layer is deposited and opened an area for the following processes of OLED device where OLED material contacts the ITO electrode is exactly the light emitting area.

Fabrication Process of OLED

For the fabrication of AMOLED, ITO electrode as the anode of OLED device must provide good transmittance and adequate electric conductivity as well as smooth surface and high work function to achieve high efficiency and stability for OLED. Beside ITO patterning, OLED fabrication processes include fabrication of multi-layer organic films, sputtering of cathode electrode, and encapsulation technology. Commonly, small molecular devices are fabricated using vacuum deposition, while PLEDs are built using spin coating and, potentially, ink jet printing techniques for the fabrication of large size displays. The smooth surface, uniformity and, compactness between films are critical for device performance. In order to give low bias voltage and provide sufficient stability at the same time, the suitable materials for cathode need to be low work function ones. Because organic materials react with moisture and oxygen actively that would lead to degradation of OLED material and result in the decrease of lifetime and emitting efficiency, they are fabricated in the inert gas atmosphere for reliable operation. As for encapsulation technology, it is a critical process because the success or failure of the encapsulation technology directly determines the success or failure of AMOLED.

1.6 Motivation

In this thesis, two topics are studied. The first topic is the systematic investigation of the conventional pixel circuit design. Dimensional effects of transistors and storage capacitor are designed and analyzed. The second topic is to propose two novel voltage driving pixel circuits with only one additional control line to compensate the electrical variation of the driving TFT using the concept of diode-connected TFT in order to improve AMOLED image quality.

- **Dimensional Effects of Transistors and Storage Capacitors on Conventional Pixel Circuit Schematic**

Although the traditional pixel circuit structure with two transistors and one storage capacitor suffers from pixel to pixel brightness non-uniformity problem due to the narrow process window of super lateral growth region (SLG), it is easy to fabricate and can be driven by a rather simple external driver electronics. Therefore, it might be a good solution for some small size application. In this thesis, a systematic study is made on the conventional basic design of active matrix pixel circuit. Dimensional effects of transistors and storage capacitor on circuit characteristics are designed and investigated by various simulation and experimental results. Moreover, different layout method related to slicing layout method of the driving transistor is also designed and introduced in the testing pixel to analysis its impact on the circuit performance.

- **Improve AMOLED Image Quality by Voltage Compensation Pixel Circuits**

Although the active matrix with LTPS TFTs is considered to be the most appropriate choice and would be the mainstream technology for full color OLED display in the future, there are several issues in developing poly-Si AM-OLED displays. Pixel to pixel non-uniformity due to the inevitable process is definitely the critical one. Therefore, many circuit designs were proposed to solve this problem. However, some of them have complicated configuration and complex driving schemes. In this thesis, two novel pixel circuit schemes both composing of five transistors and a capacitor with only one additional control signal are proposed. They employ the concept of diode-connected transistor to store threshold voltage of driving TFT. Because threshold voltage of driving TFT can be stored and held in the capacitor for the whole frame time, the brightness uniformity across the panel can thus be improved compared with the conventional two transistors and one capacitor (2T1C) pixel circuits. The comparisons between these two circuits with conventional 2T1C circuit and other circuit design using the same concept are also shown and discussed based on the simulation results of HSPICE. Through experimental results, it is verified that the proposed circuit is capable of reducing the threshold voltage variation problem of conventional pixel circuit and possessing larger output current.

1.7 Thesis Organization

In chapter two, all the pixel circuits for AMOLED were described and introduced. These pixel circuits are classified into digital driving circuit, analog driving circuit and, novel driving circuit. The detail information of compensation principle for different types with advantages and disadvantages was also discussed.

In chapter three, the conventional pixel circuit with two transistors and one capacitor (2T1C) was studied. Dimensional effects of transistors and storage capacitor were investigated and analyzed based on various simulation and experimental results. In addition, slicing layout method on driving TFT was also introduced to investigate its impact on circuit performance.

In chapter four, two novel voltage driving pixel circuits were proposed for improving the image quality for display. The concept of diode-connected transistor which is employed for compensation and the driving schemes of the two circuits were then described and introduced. After that, the performance of the proposed circuit designs and the comparisons in regarding to the power consumption and uniformity between conventional 2T1C circuit and other circuit design were shown and discussed based on the simulation results of SPICE. The compensation capability of the first proposed circuit design was also investigated and verified by experimental results.

Finally, summary and conclusions is given in chapter 5.