Printed Electronics and E-paper

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Abstract

Printed electronics is a compilation of significant developments that have contributed to changing the traditional perception of printing using paper. Printed electronics is characterized by employing common printing techniques, such as inkjet, gravure and screen printing, to print special functional inks on low-cost materials, such as plastic, paper and glass. These techniques open the doors for a wide range of low-cost manufacturing applications from flexible displays, transistors, RFID tags to interactive cloth.

This paper summarizes the overall developments of Printed electronics and then focus on Electronic paper (or E-paper) as one of its applications. In particular, this paper talks about what parts of printed electronic developments that contribute to the developments of this promising flexible display that mimics papers properties in terms of flexibility and readability and can update its contents via wireless connections.

Introduction

Printed electronics (PE) (also referred as Plastic electronics or Flexible electronics) has gained importance due its capability to utilize flexible materials such as plastic, paper, etc. to produce functional electrical devices at low cost. These devices or circuits are characterized by, beside flexibility, thin-film, lightweight, low power consumption and transparency.

PE is performed by printing several functional layers on top of each other, each with a specific position and with high - resolution. Therefore, different printing methods are operated for producing such electronic devices. The selection between them is made based on their resolution, speed, materials that are used and the requirement layers properties [1]. For instance, conventional printing processes (or mass-printing) such as gravure, flexo and offset are used for roll-to-roll printing and can achieve high printing resolution (20 µ), inkjet and screen printing are suitable for sheet-fed printing and they can achieve a resolution between 50 µ to 100 µ [2]. Consequently, due the employment of different printing methods, PE can be processed in low temperature conditions and it does not affect the environment since its use flexible material such as plastic or paper.

The printed ink consists of organic conductive or semiconductive polymers in liquid-based form. The viscosity of the ink needs to be specified depending on the printing method to achieve high printing quality, for instance low-viscosity inks are more suitable for inkjet or gravure. Moreover, additives are included with the functional ink in order to enhance their performance in terms of viscosity, surface tension, adhesion, etc [2].

Various applications have been developed at low manufacturing cost, such as flexible displays, solar cells, RFID tags, batteries, etc. due to the ability of PE to integrate flexible electronic circuits into their structure. Organic Thin-Film-Transistors (OTFT), for example, are integrated on flexible substrates as part of a special display drive circuit. This technique significantly reduces the manufacturing cost of constructing electronic paper's backplane. This study therefore demonstrates the important fundamentals of electronic paper structure.

E-Paper

Electronic paper (or E-paper) is considered one of the promising applications of PE due to its features that mimic printed paper. It employs a special ink (i.e. Electronic ink) that printed on flexible substrate such as plastic. The result is a flexible lightweight display device with a wide viewing angle and high contrast ratio at low manufacturing cost. Furthermore, demanding power when changing the displayed image makes e-paper consume low energy levels [3].

Figure 1 demonstrates the general schema of e-paper structure. The basic layers are substrate, backplane, frontplane and encapsulation.

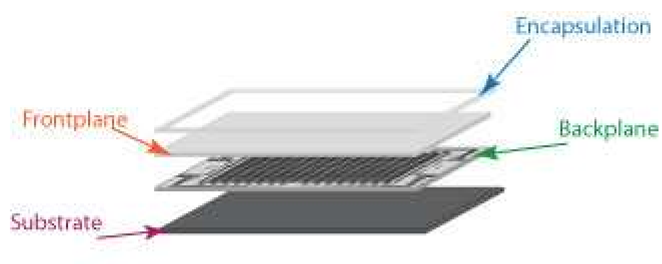

***Figure 1** E-paper device structure*

Substrates

The flexible substrate is the bottom layer of e-paper display device. It could be metal foil, plastic (or organic polymers) or flexible glass. These substrates are thin, optically transparent and have a smooth surface that helps to reduce the sensitivity of device film's electrical function, which is increased by decreasing of the film thickness. In addition, they are characterized by having low CTE (coefficients of thermal expansion) along with their dimension and thermal stability. They also act as a barrier film for permeable water and oxygen vapors, which ensures long shelf life for a device. Moreover, they facilitate supporting the device layers due to their higher elastic modulus. They can be used as electrical insulating substrates or as conductive or semi conductive substrates based on their material structure. [4]

Backplane

This layer can be thought of it as the sole of the electronic display device as it consists of the display driver circuits. It can be either a passive or active matrix backplane. The Active-matrix backplane (AM) is the most common used with flexile e-paper displays due to its high refresh rate and lower power consumption[5]. It consists of an array of Thin Film Transistors (TFT) where each pixel in the display device is addressed by at least one single TFT.

Basically, a TFT consist of four main layers: source and drain electrodes, a thin film of a semiconductor, an insulator or gate dielectric, and a gate electrode on a supporting substrate layer [6]. **Figure 2** illustrates a cross section design of two different depositing methods of TFT layers. The TFT performance is affected by the selection of its layers deposition structure.

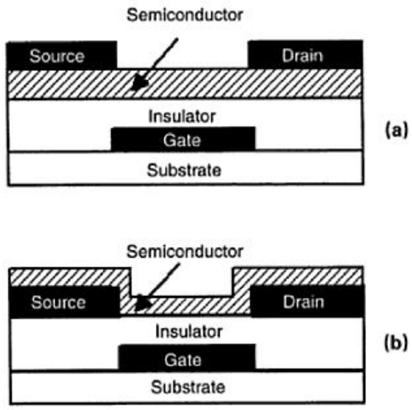

Figure 2 *Two different TFT layers constructions: (a) Top-contact device and (b) bottom-contact device [7]*

Various technologies were used to develop AM backplanes; each characterized by the substrate material and the semiconductor that is used, which influences the TFT manufacturing conditions.

Substrate

Recently, plastic materials (such as PET and polyester) and papers have become dominant materials for flexible AM backplane fabrication. These low cost materials are suitable for high speed roll-to-roll processes and they serve other critical properties in flexible displays, such as lightweight and ruggedness. Other substrate materials such as glass, steel foils or fabric are still being considered. [8]

Semiconductor

The thin semiconductor layer can be in different form such as amorphous, polycrystalline or organic. Hydrogen amorphous silicon (a-Si:H) has been the most widely used semiconductor for TFT fabrication on flexible substrates since 1990. a-Si:H is characterized by its ability to be deposited in a thin film on various substrates materials. Further, utilizing Plasma-Enhanced Chemical vapor disposition (PECVD) process to deposit a-Si:H at low temperature of 150° C or less assist reducing manufacturing cost and contribute adapting a-Si:H in large-area electronics and display applications. [9]

Another form of silicon semiconductor is Nanocrystalline silicon (nc-Si). As with a-Si:H, nc-Si is also deposited using the PECVD process. However, it has more advantages over a-Si:H, such as higher electron mobility, higher stability and it is easier to fabricate. [10]

Polycrystalline silicon (Poly-Si) is another promising semiconductor as it has a higher mobility (or device switching speed) than a-Si. PECVD, solid-phase crystallization (SPC) or Low-pressure chemical vapor deposition (LPCVD) process are used at a high temperature of 300° C to deposit poly-Si on glass. However, high temperature has a negative influence on plastic and paper substrates as it could lead to mechanical stress, therefore, a laser crystallization process is used to deposit poly-Si at low temperature of 150° C. [11]

The use of organic semiconductors was reported back in 1983. Since that time, numerous developments and enhancements were applied to organic TFT (OTFT), making it the dominant technology for promising organic electronics. The most important advantage of using organic-based materials over silicon based materials is the ability of fabricating OTFT in a non-controlled room at atmospheric temperature, which is suitable for flexible polymer substrates (plastic), in high speed roll-to-roll processes. Despite the lower electronic efficiency of organic electronics over the silicon-base electronics, their lower manufacture cost and operational lifetime contributes using them in many low-function applications (such as AM backplane) to replace expensive silicon materials. [12]

Organic materials **(Figure 3)** that are used as active semiconductors can be small molecules (e.g. pentacene and rubrene), conjugated polymers (e.g. polythiophenes, PPV, P3HT or polyacetylene), hybrid organic-inorganic structures or molecular semiconductors (e.g. nanotubes). [13]

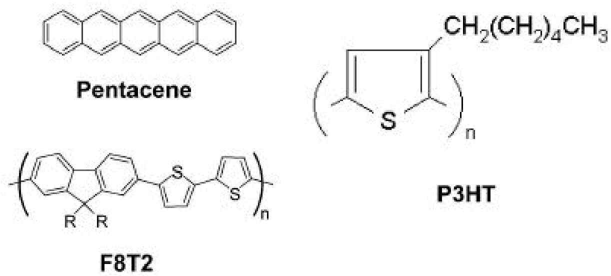

Figure 3 *Examples of smaller molecular and conjugated polymer semiconductors [8]*

Basically, organic semiconductors are fabricated in either vapor-phase process or solution-phase process [9]. Vapor-phase techniques are used for depositing the insoluble small molecular semiconductors, which include, for instance, vacuum thermal evaporation or organic vapor phase deposition (OVPD). On the other hand, dip coating and spin coating solution-phase process are utilized to deposit thin films of conjugated polymer semiconductors. The development of the solution-phase materials has contributed in utilizing common low-cost printing techniques, such as inkjet, flexo, screen printing and gravure printing processes to print organic semiconductors in a continues high-speed process.[8]

Dielectrics

This layer serves as an insulator between the active semiconductor and the gate electrode. Therefore, some requirements need to be achieved in case of choosing the appropriate dielectric materials as it influences the TFT performance. For instance, dielectric film thickness, roughness, dielectric constant, needs the ability to control leakage and withstand the TFT fabrication process. In addition, since it's located between the semiconductor and the gate electrode which creates two interfaces, some interface treatments are utilized in order to enhance the TFT performance. [14]

The selection of the gate dielectrics materials must be compatible with the semiconductor that is used. For instance, silicon dioxide (SiO_2) and silicon nitride (SiN_x) are example of inorganic dielectrics materials that are used with an a-Si TFT backplane. Vapor-phase deposition methods are utilized to deposit this kind of dielectric material. On the other hand, organic polymer dielectric materials are used with organic semiconductors. Most widely used are poly (vinyl alcohol) PVA and poly (vinyl phenol) (PVP) with OTFT. The most important feature of using a polymer dielectric is that they deposit using inexpensive solution-phase processes, such as spin coating or printing, which allow them to form smooth film, which is consistent with organic semiconductors.[8]

Electrodes

Gold (Au), platinum (Pt) and Copper (Cu) are commonly used as conductive materials for fabricating source-drain electrodes and gate electrode as well in OTFT. A solution form of these metallic materials (or the conductive ink) can be either spin coated or directly printed on the substrate, using common printing techniques to form the circuit patterns. These materials are stable to be used in the contact points between source-drain electrodes and the semiconductors and, due to the low temperature process, they can be applied on plastic substrates. In addition, sufficient circuit pattern accuracy is achieved with direct printing methods, such as inkjet, flexo, gravure, micro-contact printing and screen printing, comparing with conventional photolithography. Moreover, the use of inexpensive conductive inks with common graphical printing techniques enable reducing manufacturing costs.[4]

Frontplane

Many technologies are utilized to serve as the frontplane of the flexible display such as Electrophoresis (e.g. Gyricon, EInk and SiPix), Electrowetting (e.g. Liquivista), and many others. Despite their common features, they vary in their physical implementation.

Gyricon or Smartpaper™ was developed in 1970 at Xerox Palo Alto Research Center (PARC), by Nicolas Sheridan [15]. This technology is based on tiny pockets that are filled with oil, each individual pocket contains a bichromal ball, that is divided into two colors (black and white) and each side has an opposite electrical charge. The ball will rotate freely inside the pocket to show either black or white color to the visible surface based on the applied electric field. The pockets are suspended in a thin transparent rubber material and it's embedded between two thin and flexible plastic sheets that contain electrodes **(Figure 4)**. The image Pattern can be controlled by a passive or active-matrix backplane device by applying an electric field to the balls [16].

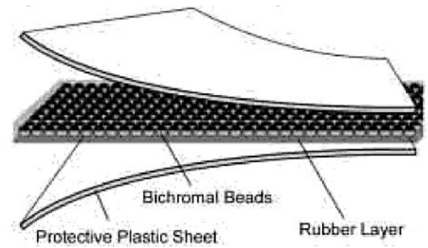

Figure 4 *Gyricon structure [15]*

Gyricon e-paper is thin, bistable, and low power consuming. It allows wireless updates, with resolutions between 200 dpi and 300 dpi [17].

E Ink was developed by Joseph Jacobson in Massachusetts Institute of Technology (MIT) Media lab and introduced in 1999 by E Ink corp. (Coburn et al, 2001). It consists of tiny microcapsules (100µ) each filled with negative (black) and positive (white) particles that are suspended in clear fluid. The affected particles will rotate to the top visible surface of the microcapsule based on the applied voltage. The microcapsules are suspended in a liquid, which is applied using screen printing to print eink on several surfaces, including plastic [18]. This surface is then laminated to a circuitry layer, which is controlled by a display driver to form the image pattern.

The most recent evolution of E Ink's imaging film is called Vizplex **(Figure 5)**. It's fabricated in a roll-to-roll process to laminate the electronic ink onto a transparent plastic frontplane coated with indium tin oxide (ITO). The ink film is then converted into sheets after combining it with thin adhesive and a plastic release sheet. TFT backplane manufacturing companies can then use Vizplex to build their display. This development leads the electronic ink to be brighter, switch faster and support 8 gray levels as well. [18]

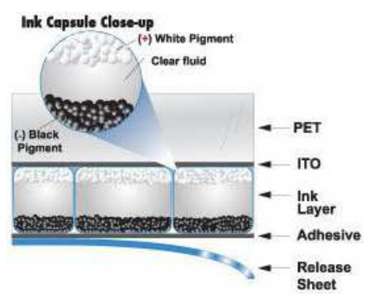

Figure 5 *Vizplex imaging film [18]*

The SiPix version of electrophoresis technology is called the Microcup® **(Figure 6)**. A Microcup® array is subjected on a flexible electrode layer that consists of polyethylene terephthalate (PET) plastic substrate coated with transparent conductor (e.g. ITO). Each individual Microcup® contains suspensions of colored dielectric solvent and charged pigmented (TiO_2) particles and it is seamless sealed with an adhesive layer. The sealing layer is then laminated on a second conducted layer (Passive or Active-matrix backplane). Based on the applied electrical field, the viewing surface can either reflect the color of the solvent or the particles.[19]

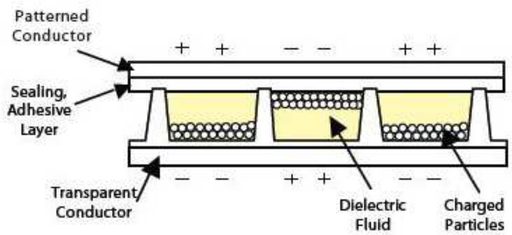

Figure 6 *Microcup® structure [20]*

A large area of SiPix's Microcup® array is fabricated in a high speed and low cost roll-to-roll lithographic or embossing process. The final Microcup film can be custom separated based on the required sizes of different display applications.

Beside their flexibility and mechanical stability, ultra thin Microcup® Electronic Paper Displays (EPD) (150µm) are capable of achieving up to 16 grayscale levels and high color saturation with more than 300 dpi resolution. [21]

Overall, despite the advantages of the electrophoresis displays, they are still suffering from lower response rates, which is required for displaying video contents. Electrowetting technology was developed to overcome this lack in electrophoresis display. This technology was developed at Philips Research in the Netherlands by Johan Feenstra and Rob Hayes. The fundamentals of this technology are based on the altering in wettability when an electrical field is applied between a hydrophobic material and a liquid causing microfluidic movements. [22]

In electrowetting displays, each pixel consists of a set of layers where the bottom layer is a reflective white substrate and could be fabricated by using a white polymer foil coated with a thin, transparent ITO electrode. An active matrix substrate could replace the bottom layer for high speed display for video contents. An amorphous fluoropolymer hydrophobic insulator is then coated over the ITO electrode. A photolithographic process is then employed to build the pixel walls, which are then filled by colored oil film that consists of dissolved non-polar dyes in alkanes. A second electrode layer would be then deposited over the oil film. This electrode layer would be water. All these layers are fabricated between two polymeric substrates (**Figure 7**). [23]

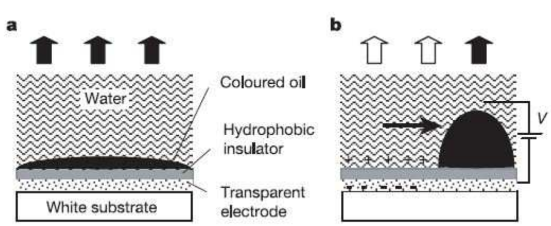

Figure 7 *Electrowetting structure [24]*

If no electric field is applied, the oil will spread out over the hydrophobic material, where the colorant of the oil will reflect the pixel color. When applying an electric field across the hydrophobic material, it will then become hydrophilic and the water will push the oil aside showing the white paper background. [22]

The current resolution of the electrowetting display is 160 dpi. In addition, for displaying video contents, electrowetting displays have the advantage over the electrophoresis displays due to its high switching speed. [24]

Encapsulating

Encapsulating all the aforementioned layers of e-paper displays with a thin barrier coating (usually ITO coating) layer has the main purpose to extend the device life. This encapsulation layer is usually made from the same polymeric material as the bottom substrate layer, which ensures maintaining the flexibility characterization of the display. [12]

Market size

Based on IDTechEx estimation, the PE applications had the fastest growing market and would project to $55.1 billion by 2020 [25]. For the e-paper display market, IDTechEx estimates that it would be subjected to $1.17 billion in 2014 and raising to $7.45 billion by 2020. [26]

Conclusions

This paper focused on presenting the basic fundamentals of printed electronic (PE) technologies and the overall structure of e-paper as one of the promising applications of PE. The possibility of printing circuits on flexible substrates, along with the development of electronic ink technology has contributed in introducing variant e-paper display products that mimic paper properties of flexibility and readability under different lighting conditions. The fabrication processes and materials requirements for the active matrix backplane were demonstrated. Also, most competing technologies behind forming electronic ink for the e-paper display were discussed.

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