Organic and Flexible Electronics

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***Abstract*—The development of organic and flexible electronics has made it conceivable to create large-area displays with quadruple the resolution, rollable solar cells thinner than paper, flexible processors used in the most unlikely of places, and hundreds of sensors sown into clothing reporting everything from pollution levels to your heart rate. The technology to develop these devices is readily available after years of research refining materials and designs to prevent organic devices from destroying themselves. This paper is a review of the operation of organic devices, the different types of materials used, the limitations that need to be overcome, compatibility to CMOS, and a discussion of current research and future prospects.**

***Keywords*—Organic, Light-emitting diode, thin-film transistor, OLED, OTFT, OLET, CMOS, light, charge carrier**

I. INTRODUCTION

Organic materials are comprised of carbon and other elements to form compounds, which may be flexible based on their chemical structure. Organic and flexible electronics are complementary factors, when melded together allow for ultra-thin electronics that are adaptable to any environment or medium. Organic materials are deposited on flexible substrates that are pliable and integrate directly into their surroundings. These organic materials drop their dependence on inflexible semiconductors, such as silicon, and instead rely on flexible small-molecules or long polymers to create the same components and devices that CMOS and other technologies have allowed in the past.

The driving force for organic and flexible electronics has been the "display," a medium that confers information to the user through a visual interface. The LCDs (Liquid Crystal Display) and LEDs (Light-Emitting Diode) of today are slowly being converted to OLED (Organic Light-Emitting Diode) displays. OTFTs (Organic Thin-Film Transistor) have slowly started to compete with CMOS in various applications, including OLETs (Organic Light-Emitting Transistor), integrated circuits and plastic processors. Roll-to-roll printing processes have enabled the production of low-cost, high yield organic solar panels and batteries. Integration of sensors and actuators to ultra-thin surfaces has created a multitude of new applications ranging from medical to structural uses. Not only has organic and flexible electronics found immediate use in existing industries, it has already started to create new industries that ten years ago, would have been considered just an "idea."

The increasing curiosity of organic electronics has not only been a key topic of interest for researchers for several decades; it has expanded to the entertainment, automotive, medical, engineering industries, and even the general public. The potential of organic and flexible electronics is enormous, yet we have little trace of its profound effects, due to the inherited difficulty with integrating organic materials with electricity to recreate the conventional products we have today. The cost of organic and flexible electronics is disproportionally higher for equivalent components and products. Researchers and various industries have been working diligently to bring forth better cost-effective processes and materials that will eventually lead to the expansion of organic and flexible electronics to many key markets.

The main advantage of organic and flexible electronics is that they can be "printed" onto sheets. This type of processing produces huge yields in a rapid manner with a convenient package. These sheets are flat, curved, bendable, and most importantly rollable, which creates vast opportunities for thinner, sleeker devices and more unique applications, such as stress sensors or medical monitoring. A key advantage for OLEDs is that they produce their own bright light without the pronounced directionality inherent in other technologies [5]. This would mean the end of backlighting, ultimately leading to a respectable decrease in power.

Figure 1. Key Organic Electronic Characteristics

Discussion of the basic operation of two key organic components, OLEDs and OTFTs will take place in section II. Implementation, discussion of materials, and fundamental limitations is available in section III. Section IV discusses the coupling of organic and flexible electronics with current CMOS technology and how it compares to it in terms of performance. Current research, market availability, and potential uses of organic and flexible electronics are found in section V.

II. STRUCTURAL AND OPERATIONAL PRINCIPLES

Because of the large amount of organic devices currently under development, only the two most prominent devices, OLEDs and OTFTs will be discussed in detail in this section.

A. *Organic Light-Emitting Diodes (OLEDs)*

OLEDs are typically made of six layers, although usually the ETL and EML layers are now commonly one layer. A substrate such as plastic or glass is used as the base for which all other materials are stacked upon. The layers are laid on the substrate using a variety of methods, including vacuum deposition, spin-on techniques (involves spinning the substrate), dry transfer (xerography), and inkjet printing [5]. Each layer could be laid on differently depending on the properties of the material used for that layer, and its neighboring layers.

One type of OLED, called small molecule OLED, utilizes tiny engineered molecules to create the typical OLED. The more prominent type, polymer OLEDs follows a similar procedure for layer application. Polymers generally use less power due to their simpler layer structure and higher conductivity, which allows them to operate at 2-5V, which is 1-2V lower than small molecule OLEDs [5]. OLEDs are grown (deposited) on a substrate to form a multilayer structure of about 100 nm thick [5]. The substrate is first coated with a transparent conducting electrode, such as indium tin oxide (ITO) or polyaniline to form the anode [5]. The HTL (Hole Transport Layer) is typically made of chemicals called diamines [5]. The EML (Emissive Layer) is deposited onto the HTL layer. This layer usually doubles as the ETL (Electron Transport Layer) [5]. Finally, the cathode is made of a low work function material such as calcium or magnesium-silver [5]. The cathode must have a low work function in order to facilitate the movement of electrons to the ETL layer. The use of calcium or magnesium-silver creates an opaque layer, meaning the OLED only emits light through the anode. There have been several instances where a transparent cathode material has been used, which allows the OLED to transport light through both, the anode and cathode. This makes the entire OLED transparent. The entire structure is around 100-500nm thick, about 200 times thinner than human hair.

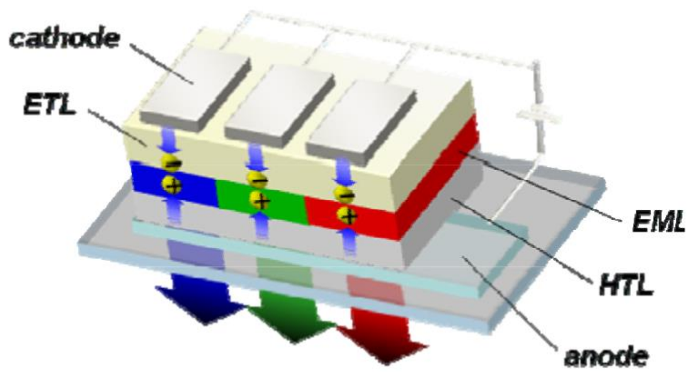

Figure 2. OLED Structure, ETL (Electron Transport Layer), EML (Emitter Layer, HTL (Hole Transport Layer)

Both polymeric and small molecule OLEDs operate by accepting charge carriers of opposite polarities, electrons and holes, from the cathode and anode contacts, respectively [5]. An applied voltage forces the carriers into the recombination zone, where holes jump from the HTL to the ETL/EML, combine with electrons, and form an exciton. Each four hole-electron pairs form one singlet and three triplets [5]. The singlet recombines within a few nanoseconds and emits a photon. The triplets take around 1ms to 1s before they emit heat primarily. This reaction is only 25% efficient. To boost efficiency, the organic material is doped with iridium or platinum, which allows the singlet/triplet mix to emit light within 100ns-100us, leading to an emission called phosphorescence [5].

Colors are made by doping the organic ETL layer with an EML. Green is made by doping the Alq_3 ETL layer with an iridium phosphor or a florescent dye. Blue is created by mixing a pigment called perylene with an ETL known as CBP. Alq_3 or CBP, doped with Lanthanide compounds and porphyrin pigments creates red. These colors for the three primary RGB colors.

There are two common drive circuitry implementations for OLEDs: Passive Matrix (PMOLED) and Active Matrix (AMOLED), both of which have their own unique advantages and disadvantages. PMOLEDs depend on outside circuitry to drive them, notably CMOS circuits. AMOLEDs have drive circuitry directly built into the substrate, thus removing the dependence on outside circuits. Initial circuits constituted of TFTs (Thin-film transistor) made from amorphous silicon (a-Si). Recent developments in OTFTs has allowed for complete integration of organic LEDs and transistors on one substrate to form a truly organic, flexible active matrix. There has been some work on creating a transistor that emits light, called an OLET. This would eliminate the need for an active matrix, because the transistor drives the OLED itself [1].

These two implementations, PMOLED and AMOLED can be further subdivided into either transparent or top-emitting structures, which are created depending on the physical properties of the components of the OLED. All of the layers are usually transparent, except for the cathode. There has been some successful experimentation with transparent cathodes with low work functions. The majority of the light produces by an OLED is directed towards the cathode, but typical OLEDs have mirrored cathodes, which redirect the light through the anode. By having the light escape through the cathode as intended, the light output is actually increased. Researchers have developed OLEDs with transmittances of 50 – 70% through the cathode, producing 15 cd/A at $5mA/cm^2$, without damaging the organic layers [8].

The main advantage of OLEDs is that they produce their own light, unlike LCDs, which depend on a white backlight to provide an image. Without the backlight, the LCD would look blank, even though an image is constituted in the liquid crystal layer. This amounts to an immediate power savings. OLEDs also provide good color saturation and clarity. It is also sunlight readable unlike many LCD technologies [12]. They can be stacked on top of each other to create a three-in-one pixel (Red, Green, Blue), which virtually triples the resolution. They can also be made transparent, which allows them to be used on glass for advertising and heads-up displays in automobiles.

B. *Organic Thin-Film Transistors (OTFTs)*

OTFTs are made in the same way that typical thin-film transistors are made. The organic material consists of small molecules or polymers, similar to OLEDs. The gate electrode is first deposited on a substrate, such as glass or plastic [5].The gate insulator is deposited next, which can be an organic or an inorganic dielectric. The source and drain electrodes are deposited on the gate dielectric. Finally, the organic channel is placed on top. Deposition of these layers can be done using standard photolithographic techniques [5]. Other successful methods, such as injection molding and inkjet printing have created the potential to produce very low-cost devices.

OTFTs work just like any other transistor. A charge is placed on the gate, which induces a conductive channel between the drain and source. Although these transistors are relatively slow, their cost could outweigh performance needs in many applications including producing large backplanes for displays. Researchers and industry are working on improving performance with other techniques and materials, including creating a FinFET (Fin Field-Effect Transistor) version of the OTFT, where the gate electrode and dielectric are placed on both sides of the organic channel.

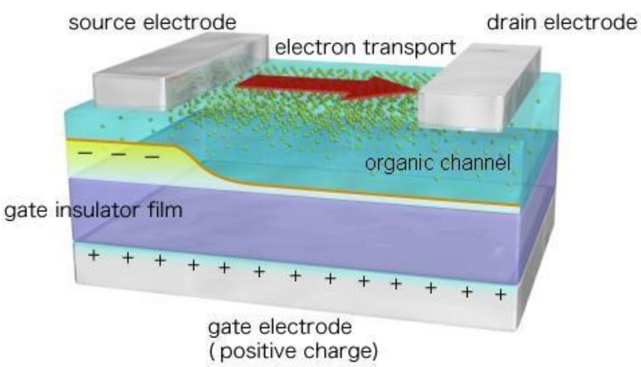

Figure 3. OTFT Structure

OTFTs don't suffer from threshold voltage instability issues, which are critical in supplying consistent current to components, such as OLEDs. They are easily applied to substrates at low temperatures, which is a challenge for conventional TFTs. They can be made into light emitting transistors, which minimize the power and number of transistors needed for active matrix backplanes in displays. The driving force behind OTFTs is the ability to create large-area electronics on flexible substrates.

III. Materials and Limitations

This section will discuss current technology used in organic and flexible electronics today and discuss the limitations of each. A discussion of key limitations of OLEDs and OTFTs will also be discussed.

A. Amorphous Silicon (a-Si)

Amorphous silicon or Hydrogenated amorphous silicon (a-Si:H) commonly used today, is the key element of the active matrix backplanes for LCDs. This material requires high temperatures during deposition, which limits what type of substrate can be used, such as PEN (Polyethylene naphthalate) and PET (Polyethylene terephthalate), both commonly used to make soda bottles [12]. This has ruled out flexible displays for many years, until researchers developed novel ways of creating a-SI:H TFT backplanes using low-temperature processes. Although a-SI:H TFTs seem like a perfectly good solution to creating flexible displays with active matrices, they have large threshold voltages shifts, which reduces the drive current to devices, such as OLEDs. To reduce threshold shifts, the process temperature needs to be increases, which rules out many plastic substrates [12]. Eventually, researchers and industry leaders developed high temperature plastics that can withstand high processing temperatures of 250-280°C [12]. Another issue with TFTs is that few have developed flexible driving circuitry for displays. It has been concluded that the low mobility of TFTs and high threshold voltages shifts have relegated these devices to sub-video rate applications, such as occasional updating, as in advertisements, maps, e-readers, and electronic newspapers [12].

B. Polysilicon

Poly-Si TFTs are processed at higher temperatures by re-crystallizing a-SI:H using lasers, which stabilizes threshold voltage shifts and increases mobility to over 100 $cm^2/V{\cdot}s$ [12]. Poly-Si TFTs can be made in both n-type and p-type, which makes them useful for backplanes and CMOS circuitry. Although these devices have good performance, the processing and substrates costs are substantial and are not economical for cell phone displays or RFID tags.

C. Organic Thin-Film Transistors (OTFTs)

OTFTs can be processed under low temperatures, which allow them to be printed onto many plastic substrates, using many solution and vapor deposition techniques. Implementing roll-to-roll processing would drive down the cost of production considerably. Mobility's of 0.1 to 5 $cm^2/V{\cdot}s$ can be achieved, which fall into the useful realm of display backplanes and other slow rate circuits.

OTFTs are highly sensitive to elements such as oxygen, water, dust and must be contained within an inert material. Sometimes and inert gas like nitrogen is sandwiched between the OTFT and covering [5]. This is true for OLEDs as well.

OTFT performance is mainly limited by the electron/hole nobilities of the organic channel. Most OTFTs have a mobility of about 1 $cm^2/V{\cdot}s$ at room temperature, which is actually equal to amorphous silicon TFTs used in today's LCDs. Although polymers are better for OLEDs because of their simpler structure and higher conductivity, they have poor carrier mobility in OTFTs, due to irregularity of their ordering, thus limiting the speed of OTFTs. Small molecule OTFTs are quicker because they tend to be more ordered due to their smaller size.

Recent work with polymer OTFTs lead to the creation of a 326 OTFT code generator with 2um gates. These transistors were able to achieve mobility rates of 3-4 $cm^2/V{\cdot}s$ and operate ate 200 Hz, which is more than enough for displays [5].

D. Single Crystal Silicon

This technology has implemented high-speed circuits with mobilities greater than 500 $cm^2/V{\cdot}s$. Frequencies of 500 MHz have been achieved by printing microstructured silicon (us-Si) by dry transfer or solution-based techniques on flexible substrates to produce high performance TFTs [12].

One study reported a mobility of 60 $cm^2/V{\cdot}s$, with a threshold voltage of 0.8V [13]. These results were marred by the fact that Single Crystal Silicon TFTs are just as susceptible to threshold voltage shifts as a:Si:H TFTs. Voltage shifts of 4 - 8V were reported for positive and negative gate voltages at 30V [13]. Although these shifts are rather large, TFTs used in displays are usually operated at voltages of 10V or lower, where threshold shifting is relatively stable. These TFTs may be good for displays, but their high mobility and frequency response would not be of much benefit in higher voltage applications.

E. Mixed Oxide Thin Film Transistors

IZO (Indium Zinc Oxide) TFTs have shown promise in terms of better mobility, higher current densities, and better stability compared to a-Si:H TFTs [12]. These TFTs are naturally transparent, which makes them even more appealing due to interest in developing transparent electronics on large panels, such as windows and heads-up displays. Threshold shifts of less than 1.5V were measured over 27 hours with 20V on the gate [12]. AC stress tests over 365 hours have also shown stable outputs, but degradation of the noise margins is readily apparent.

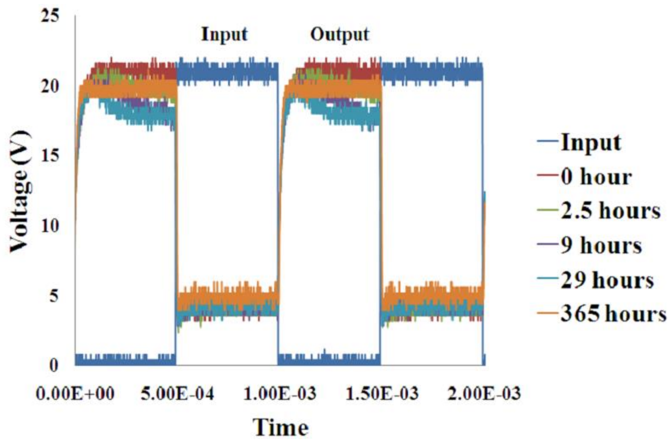

Figure 4. Digital Inverter using IZO TFTs

F. Organic Light-Emitting Diodes (OLEDs)

OLEDs use many different types of materials for the anode, HTL, EML, ETL, and cathode. New substrates such as Corning's Willow glass allows for higher processing temperatures and a smoother surface, which improves the overall effectiveness of the OLED. Even with these improvements, OLEDs still fall short in a number of areas.

OLEDs must be manufactured in clean facilities. Contamination of the substrate by dust and shorts caused by pinhole effects can inflict havoc on the life of an OLED. The chemicals involved in producing colors can change the device efficiency and reliability in an unpredictable manner [12]. Stacking of materials to create a pixel with all three colors, RGB can create unwanted cavities, which alters the emissions of the OLED. Controlling the thickness and shape of the materials deposited on the substrate is an ongoing problem. Exposure to air, even for a few hours can cause massive degradation, which is why OLEDs must be encased in an inert atmosphere to bring about useful lifetime.

Studies on OLED lifetime have found that reducing the amplitude of the current and its duration to an OLED can improve the lifetime drastically. This can be achieved through the Multiline Addressing Scheme (MAS), when software runs and algorithm to find the best way to turn on rows and bias columns efficiently to minimize on-time [4]. Balancing charge carriers to prevent charge accumulation from electrochemically degrading various layers is also important [4]. Balancing the ratio of the recombination zone can also improve lifetime.

Table 1. Intrinsic and Extrinsic Lifetime Factors

Intrinsic	Extrinsic
1. Electrochemical (oxidation, reduction)	1. Encapsulation (H_2O, O_2, etc.
2. Thermal	2. Impurities
3. Interfacial (cathode delamination, etc.)	3. Fabrication environment (dust, etc.)
4. Photochemical	4. Substrate (roughness, etc.)
5. Carrier/Charge Balance	5. Operating conditions

Developing reliable organic LEDs and transistors is a challenge due to the high electric fields (1-5 MV/cm) required to create charge conduction in organic materials. The only reason OLEDs and OTFTs operate at low voltage is due to their extreme thinness. Although these ongoing problems have placed a burden on the industry, many have overcome them to produce long-lasting OLEDs and OTFTs

IV. Compatibility with CMOS

CMOS (Complementary Metal-Oxide Semiconductor) technology has been successfully interfaced with organic LEDs and transistors. Passive matrix OLEDs are usually coupled with typical CMOS integrated circuits. Active matrix OLEDs utilize TFTs to turn on OLEDs, but external circuitry may still be required. The integration of OTFTs electronics onto flexible materials is ongoing. There have been attempts to create CMOS-like TFTs using polysilicon TFTs. One group developed an inverter with a high slope and good swing [6].

Others have tried creating "Pseudo-CMOS" circuits using either p-type or n-type TFTs, such as IZO, n-type and SAM (self-assembled-monolayer), p-type organic TFTs. They achieved circuits with comparable performance to CMOS by avoiding the use of the respective technologies unstable counterpart [11]. Some have successfully created Hybrid (CMOS) circuits by using an n-type TFT (a-SI:H, IZO) and a p-type (Pentacene) OTFT together. These circuits outperformed standard a-Si:H TFT circuits because of their more stable threshold voltages [12]. Another group decided to create an ambipolar FET using an n-type metal-oxide transistor and p-type organic semiconductor and were able to achieve an electron mobility of 13.8 $cm^2/V\cdot s$ [1]. They were also able to demonstrate electroluminescence by using tetracene as an emitting layer to form a light-emitting transistor.

V. Current Research and Future?

The number of implementations for organic and flexible electronics seems to be endless. A European group announced the creation of a plastic processor, containing 4000-transistors. It was able to execute six instructions per second [3]. Four of these processors stacked on top of each other would equal the thickness of a standard piece of paper. Another team has developed self-assembling organic nanowires used to bridge the gap between two electrodes, with the hopes of replacing brittle metal interconnects in flexible electronics [9]. Graphene has been proposed to be a replacement for the fragile ITO (iridium tin oxide), a transparent material used for anodes in

OLEDs [7]. Electric cotton has been developed to create a seamless interface between clothing and flexible electronics [10]. Others have worked on the characterization of flexible electronics, by building a bending apparatus, to help engineers design useful and comfortable flexible electronic products [2].

ACKNOWLEDGMENT

This paper on Organic and Flexible Electronics was submitted as a term paper for ESE 585: Nanoscale Integrated Circuit Design, conducted by Professor Emre Salman at Stony Brook University.

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