Organic Thin-Film Transistors for display applications

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Abstract

We review the state-of-the-art performance of organic transistors and circuits. From this perspective, we assess the performance of organic thin-film transistors in displays. We focus in particular on the use of OTFTs for pixel engines for active matrix emissive OLED flat panel displays. We discuss the required addressing mode, circuit topology, layout and drive scheme that allow to reach the desired frame rate and to control the grey levels against the threshold voltage dispersions of OTFTs and OLEDs.

1. Introduction

Organic Thin-Film Transistors (OTFT) have today been integrated into circuits of small to medium [1,2] complexity, up to about a thousand transistors. A main driver for this evolution is the low potential cost of organic TFT technology, accompanied by a short cycle time from design to product. Another potential benefit is the possibility to fabricate circuits over large areas. This latter is required for e.g. pixel engines of active matrix displays. Today, prototype active matrix pixel engines for liquid crystal displays (LCD) have been realized. In this presentation, we review the main properties and shortcomings of organic thin film transistors and circuits, and relate these to their use in active matrix displays, in particular also OLED displays.

2. Performance of OTFTs

Two classes of conjugated organic materials are widely used as semiconductors: polymers and small molecules. In addition, other types of materials like discotics [3] and filled polymers [4] are subjects of research.

2.1 Polymers

Many types of polymers have been proposed in recent years. Regioregular polymers like poly(3-alkylthiophene) and in particular poly(3-hexylthiophene) P3HT were the first to show fairly high mobilities, of the order of 10^{-2} cm^2/Vs to 10^{-1} cm^2/Vs. Data showing higher mobilities are available [5]. The useful limit is not exactly known, because it is a fact that in semiconductor polymers the mobility and the background conductivity are related to each other [6], both increasing with increasing intentional or unintentional doping of the material. Poly(9,9-dioctylfluorene-co-bithiophene F8T2 [7] has recently received considerable attention, despite the lower mobility (10^{-3} cm^2/Vs to 10^{-2} cm^2/Vs) as compared to P3TH, because of its better stability. Apart from stability and mobility of the materials, the value of the threshold voltage, the subthreshold slope and the on/off current as well as the reproducibility of these parameters are of prime importance. Values reported for P3TH are V_T = -1 V. and Ion/Ioff = 10^3-10^4 [5]. For F8T2, reported values are: S ≈ 2 V/decade, V_T =-10 V and Ion/Ioff > 10^5 [7]. Fully functional reasonably complex circuits have been demonstrated with organic polymers [1,2]. Functional circuitry in which a simple unit cell is reproduced over cm^2 areas has also been shown [8]. However, the reproducible fabrication of more complex circuits over large areas still proves a challenge today.

2.2 Small molecules

Small molecules are usually thermally evaporated from a heated source in vacuum onto a substrate. Depending on the evaporation conditions, the molecules can form an amorphous or polycrystalline film. The crystal structure is well-known and is in part responsible for the electrical properties of the films. For films of ultrapure material, it has been shown that charge transport in polycrystalline organic semiconductor films can be bandlike at room temperature [9], reaching a value of 1.5 to 3 cm^2/Vs at 300 K. However, in most cases it is limited by hopping from shallow traps or by thermionic emission over grain boundaries [9]. Original work on thin films and thin-film transistors of small molecules was done with sexithiophene (6T) [10]. More recently, pentacene has been shown by several groups to be a superior material in terms of mobility [11,12]. Threshold voltage control remains a challenge, as several groups report pentacene transistors with depletion mode as well as enhancement mode characteristics, and with in general threshold voltages that are not reproduced better than within a few Volts. On/Off current ratio's can be quite good, typically 10^6 to 10^8.

3. Display application

The first potential use of organic transistors in displays is for replacement of amorphous silicon in the pixel engines of active matrix displays. A distinction is to be made between liquid crystal displays and emissive (e.g. OLED) displays. More speculative is to replace the row and column drivers by organic technology.

3.1 Liquid Crystal Displays

Prototype active matrix polymer-dispersed liquid crystal display (PD-LCD) driven by a polymer transistor per pixel has been recently demonstrated [8]. The display characteristics are: 64 X 64 pixels, 256 grey values, 50 to 100 Hz refresh rate limited by transistor performance. This demonstrates the potential of organic transistor technology for display applications. A small molecule pixel engine has also been demonstrated [13].

3.2 Emissive displays

The requirements for emisive displays is more stringent and complex than for LCD displays. First, the emissive pixel requires a current rather than a voltage control. Further, the threshold voltage dispersion of the transistors need to be compensated by a

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multi-transistor per pixel engine, possibly enhanced by a special drive scheme. In the following paragraph, we analyze the requirements imposed on the pixel engine and assess whether organic transistor technology of today can comply with these requirements.

4. Actve matrix pixel engine with OTFTs

4.1 Initial assumptions

We perform some first-order calculations to assess the use of OTFTs for active matrix OLED displays. The assumptions concerning technology are summarized in table 1.

Table 1 : technology assumptions

OTFT		OLED	
Mobility	1 cm^2/Vs	Max brightness	100 Cd/m^2
V_T	-1 V	Efficiency	2 A/Cd
I_{on}/I_{off}	10^7	Emission through top	
L_{min}	10 um or 5 um		
t_{diel}	200 nm		
ε_{diel}	3.4		

The requirements for the display are assumed to be the following:

- Frame rate: 100 Hz
- 128 “grey” values
- Pixel area: better than 100 um X 100 um per color, i.e. 300 um X 100 um per pixel
- 3 colors
- Number of pixels: 1000 X 1000

The mobility assumed in Table 1 implies that the organic technology is evaporation of a thin film of small molecules rather than solution processing of polymers.

Printing is often quoted to be a technology of choice to fabricate organic transistors. With the present state of the art of printing, however, it will likely not be posible to reach the required transistor performance. Indeed, the gate-source and gate-drain capacitances of the transistors have to be as small as possible. In a printing transistor fabrication process, the gate-source and gate-drain overlaps can be large. Assuming a 5 µm resolution process that results in an overlap of 5 µm, an oxide thickness is 200 nm and a transistor width of 50 µm, the gate-source overlap capacitance, C_{GS}, is 38 fF. For 1000 rows, this results in 38 pF per data line, which is far too large. In a photolithographic transistor fabrication process this capacitance can be significantly smaller. In the ideal case, there is only a fringing capacitance. This can be achieved using a self-aligned lithographic process such as proposed in [14]. If the thickness of the gate metal is 100 nm, the oxide thickness is 200 nm and the transistor width is 50 µm, then C_{GS} is 0.77 fF. For 1000 rows, this makes a reasonable 0.77 pF per data line.

4.2 Pixel engine

Studies of possible pixel engines using polysilicon have shown that schemes with two transistors per pixel are sensitive to threshold voltage variations. Schemes with four transistor per pixel have therefore been proposed [15]. A configuration that requires minumum control lines is proposed by Hattori [16]. We here propose a variation to this scheme, shown in Fig. 1.

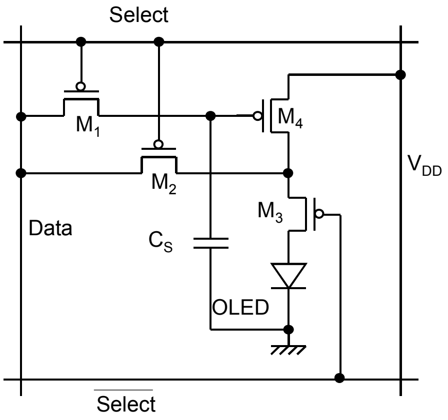

Figure 1 : Proposed pixel engine

The layout, including the positionig of control ines, power and ground, is shown in Figure 2.

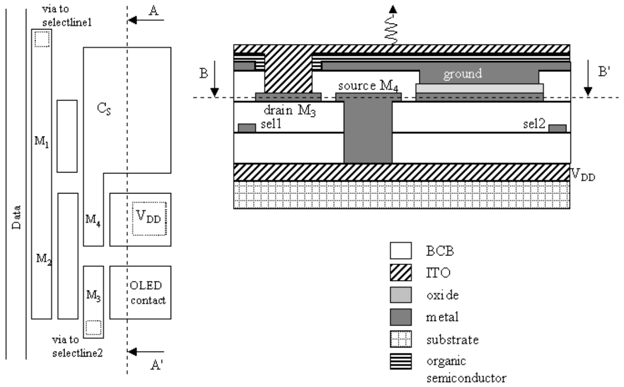

Figure 2 : Layout of the pixel driver circuit. (a) Top view BB’ of the layout. (b) Side view AA’ of the layout.

The circuit contains a number of control lines (select, NOTselect), data lines, power and ground. It is realistic to propose to lay these out into two layers. The technological option assumed is one where the dielectric between these layers is 5 µm thick and with $\varepsilon_r = 2.6$ (data of benzocyclobutene BCB). For 10 µm wide data and select lines, the parasitic capacitance becomes about 10 pF for 1000 lines. When adding the gate-surce overlap capacitances of the pass transistor (2 X C_{GS}) and the charge-storage capacitance C_s of the order of 1 pF, the total data-line capacitance is of the order of $C_{DATA} = 3.4$ pF. A similar reasoning leads to a select line capacitance $C_{SELECT} = 6.5$ pF.

Further remark that we assume that the complete area can be used for the fabrication of the OTFT pixel engine. Because of non-transparent regions, we therefore assume that the OLEDs are top-emitting.

4.3 Driving scheme

Simulations of the performance and dimensioning of the circuit of Fig. 2 have been done with the SPICE circuit simulator.

For 128 grey levels, the accuracy of the gate voltage control of the transistor controlling the current through the OLED (i.e. M4) has to be 27 mV. With an Ion/Ioff ratio of 10^7, the storage capacitance C_s is to be at least 1 pF. With a current driving scheme, the time to charge C_s from a maximally bright pixel ($I_{OLED} = 2\ \mu A$, $V_{M4} = 16$ V) to an off pixel ($I_{OLED} = 0$ nA, $V_{M4} = 24$ V) with an accuracy of 27 mV (V > 23.973 V) is too long: 1.25 ms.

A solution can be proposed in which the driving scheme is divided into two parts, a voltage-driven part and a current-driven part. In the first part the gate of drive transistor M_4 is precharged with a voltage estimated to make M_4 drive the desired current through the OLED. This voltage does not take the threshold voltage dispersion into account. The voltage charging is faster than the current charging could be. In the second part the drive current only has to charge a small voltage variation ΔV on the gate of M_4, i.e. the threshold voltage dispersion of M_4, ΔV_{T4}.

4.4 Results

Mimimum feature size (minimum transistor gate length), drive voltage, pixel size and maximum achievable brightness are interrelated. From SPICE simulation results, the relationships can be described by the graph of Figure 3 for a supply voltage of 25 V.

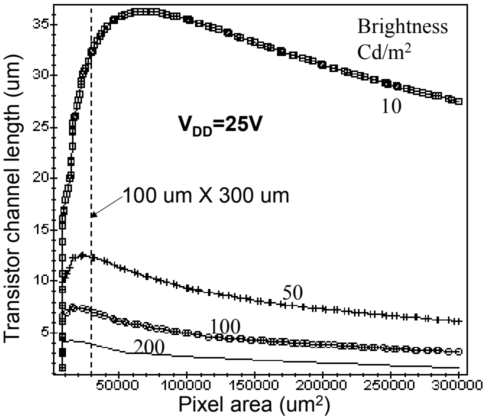

Figure 3 : Relationship between brightness, L_{min} and pixel area for V_{DD}=25 V

In a 10 micron technology (L_{min}=10 um), a luminance of 100 cd/m^2 cannot be achieved with 25 V supply voltage. It is required to provide at least 37 V. The smallest pixel area at which a brightness of 100 Cd/m^2 can be achieved with 37 V is 245 um X 82 um. In a 5 micron technology (L_{min}=5 um), a luminance of 100 cd/m^2 can be achieved with a minimum supply voltage of 19 V for a pixel with an area of 203 um X 68 um.

5. Conclusions and outlook

Organic transistor technology has potential for active matrix displays. This is not only so for liquid crystal displays, but even for OLED displays. We show that the pixel engine of a 1000 X 1000 pixel (color) OLED display with resolution of 300 um X 300 um per three-color pixel could be achieved with an equivalent of pentacene transistors. The required technology is quite relaxed, namely 5 to 10 micron gate lengths, provided that the overlap capacitances of source-gate and drain-gate are minimized.

It remains to be seen whether this can be done by a printing process. The expected large threshold voltage variability can be taken care of by using more complex drive circuitry. Polymer transistors with lower mobility than small molecule transistors have been demonstrated for LCD displays, but their current performance does not seem compatible with the requirements of OLED displays.

The use of organic transistors to integrate row and column drivers together with the pixel engine seems not possible at present, and will require further evolutions in the performance and technology of organic transistors.

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