TFT Interfaces for High Sensory Resolution at Ultralow Power

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ABSTRACT

We review design and materials selection strategies for ultralow power operation of thin film transistors. Issues in TFT process-integration that can adversely result in high operating voltage are examined along with routes to suppress interface trap density at the active channel/gate dielectric layers to lower the operating voltage.

1 Introduction

A key design consideration in flexible electronics, particularly for wearables and sensing applications, is low voltage, low power operation. This requirement not only serves to maximise battery lifetime but crucially ensures operational stability of thin film transistor (TFT) circuits and systems [1,2]. Ultralow voltage/current operation is especially important in sensor interfaces so as to achieve a high resolution of the sensory signal.

This presentation will review TFT design and materials selection strategies for low voltage, low current operation. We examine the main processing issues that can lead to a high gate voltage operation, and discuss processing routes that suppress the interface trap density. This serves to reduce the voltage drop across the active channel and gate dielectric interface, and hence the operating gate voltage. Recent advances in low-voltage thin-film transistors show it is possible for the subthreshold slope to approach the thermionic limit, q/k_BT. Based on these studies, we present an all-inkjet-printed ultra-low-power high-gain amplifier, applied to eye movement tracking by detecting human electrooculogram signals.

2 TFT Operating Voltage and Subthreshold Slope

The operating voltage can be indirectly specified through its subthreshold slope, which describes the slope of drain current modulated by the gate voltage. Here the switch-on mode of a transistor can be defined as the transition from the OFF- to the ON-states by the following simple form for the subthreshold slope:

$$SS = \ln 10 \frac{k_B T}{q}\left(1 + \frac{q^2 D_t}{C_i}\right)$$

Here, k_B is Boltzmann's constant, T the absolute temperature, q the elementary charge, D_t the trap density, and C_i the unit-area capacitance of the gate insulator. We see that it is important to reduce trap density D_t or increase unit-area capacitance of gate insulator C_i to lower the subthreshold slope. Increasing C_i has been widely adopted in vacuum-deposited devices, such as semiconductor oxide TFTs by using an ultra-thin dielectric layer or a high-*k* dielectric material, which may not be as convenient in solution processing. Alternatively, reducing the trap density D_t to lower the subthreshold slope [3] remains a viable route, but can be quite involved by virtue of process challenges.

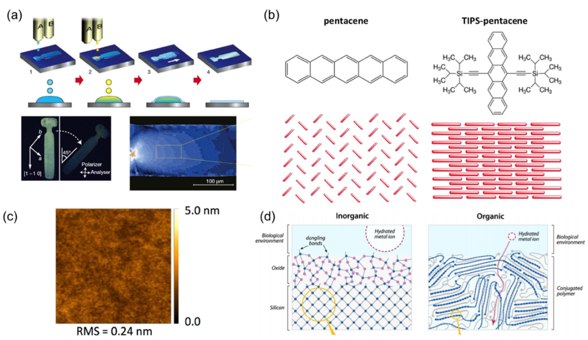

Figure 1. Traps density reduction at the dielectric-semiconductor interface in organic TFTs [4].

3 Low-voltage Organic Thin-Film Transistors

Organic thin-film transistors (OTFTs) have attracted considerable attention for newly emerging applications that go beyond displays. Examples include flexible wearables, biosensors, smart packaging, radio-frequency identification tags, to name a few [1,4]. One of the key advantages of OTFTs is that they can be manufactured by a printing processes, which offers great advantages such as low cost and low chemical wastage. However, there are several critical issues in typical printed OTFTs. These are to do with the high operating voltage and poor operational stability, thus limiting the products that can be offered. The two aforementioned issues originate from the same source, i.e., traps. Traps are formed in the devices during the printing process and are found mainly at the semiconductor/dielectric interface and in the bulk semiconductor channel material [5].

To optimize the fabrication of all-inkjet-printed

OTFTs, we have compared different semiconductor and dielectric materials, as well as different solvents for formulating inks. We found that using a solvent with a higher boiling point in the semiconductor ink could help the crystallization of small-molecule semiconductors [6]. In addition, the selection of semiconductor materials is also important. The trap density can be significantly reduced if the semiconductor material used forms large crystallites [5]. As for the dielectric materials, we found that Lewis-acid monopolar dielectrics can be effective in preventing water molecule absorption and providing a good surface for other organic inks to be printed on top, thereby enabling all-printed OTFTs with good stability [7].

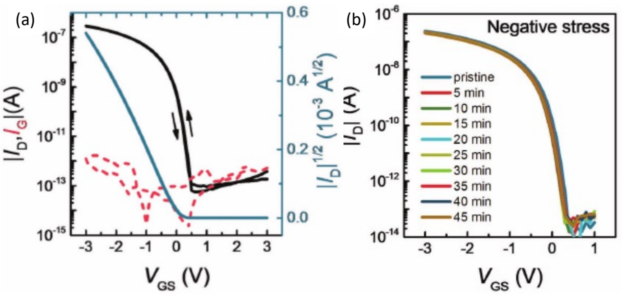

Figure 2. Transfer characteristics and bias-stress stability of an all-inkjet-printed OTFT [7].

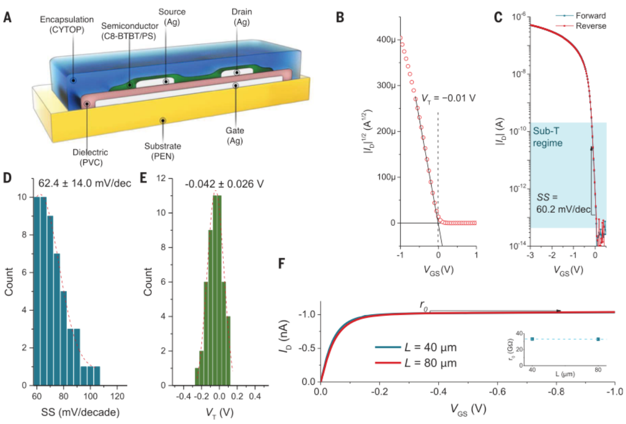

Figure 3. Schematic cross section and electrical characteristics of the fabricated OTFT [5].

The all-inkjet-printed OTFTs presented here have a bottom-gate bottom-contact structure [5]. As shown in Fig. 3, the optimized device used 2,7-dioctyl[1]benzothieno[3,2-b][1]benzothiophene (C_8-BTBT) blended with polystyrene (PS) for the semiconductor, polyvinyl cinnamate (PVC) for the dielectric, silver (Ag) for the gate/source/drain electrodes, and CYTOP for the encapsulation. The fabricated devices demonstrated a small subthreshold slope of 60.2 mV/dec, which is close to the thermionic limit. In addition, the bias-stress stability was highly favourable in that the threshold voltage shift was only about 30 mV during a 60-min negative bias-stress period. The device had negligible changes in transfer characteristics when stored in the ambient for over a year. These results demonstrate the promise of this device for low-voltage operation for real life applications.

4 Ultralow Power TFT Sensor Interfaces

In addition to lowering the overall voltage drop by reducing the trap density D_t at the semiconductor-dielectric interface, the TFT can be operated in the deep sub-threshold regime, where the operating current is close to its OFF-state value [8]. Here, choice of a wide bandgap channel material is highly desirable in view of the low thermalization current. In addition, this provides the flexibility needed to achieve good Schottky behaviour, wherein the current-voltage characteristics are virtually independent of bias and channel geometry. Fig. 4 illustrates an example of a Schottky TFT realized using vacuum-deposited semiconductor oxide technology. The TFT yields characteristics that are very attractive. Its infinite output resistance gives rise to high intrinsic gain, making it particularly suited for bio-sensing in wearables. The operating current and voltage are low, and accordingly so is the 1/*f* noise, which results in high signal resolution.

We characterized the performance of this device under subthreshold operation [5]. Due to the steep subthreshold slope, the fabricated OTFT demonstrated a large intrinsic gain of 1100 V/V in the subthreshold regime, where the operating current can be exponentially reduced, and so can the power consumption.

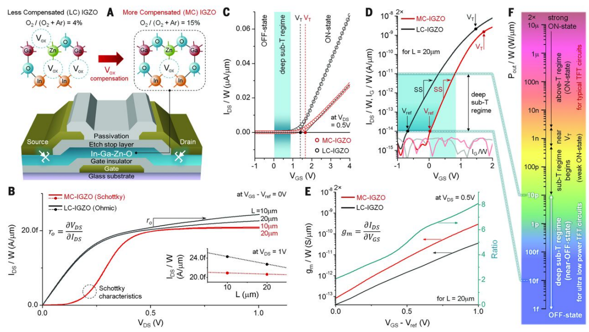

Figure 4. Device structure and basic electrical characteristics of a Schottky-barrier TFT realized using vacuum-deposited semiconductor oxide technology [8]

5 Sensor Interface with High Sensory Resolution

Based on the considerations presented above, we demonstrate a subthreshold common-source amplifier [5]. The amplifier showed high voltage gain of 260 V/V and low power consumption of < 1 nW. We applied this amplifier to eye movement tracking by measuring subtle electrooculogram (EOG), an electrophysiological signal, which is usually below 1 mV. The amplified EOG signal has an amplitude of around 300 mV. Such a relatively large amplitude of post-processed electrophysiological signal offers higher immunity to noise and EMI during transmission between the signal pick-up and read-out points. Of significance is the low power consumption. The circuit can potentially operate from energy acquired from microharvesters.

6 Conclusion

For wearable and implantable devices, low voltage, low current operation is essential. In particular, Schottky-barrier TFTs operating in the deep-subthreshold regime constitutes a highly desirable platform, in view of low noise at low currents, hence yielding high sensory resolution. In deep-saturation, the Schottky-barrier TFT has a saturation drain current that is independent of drain voltage giving rise to an infinite output resistance and thus a high intrinsic gain. Such a device architecture with oxide TFTs constitutes a new design paradigm for sensor interfaces and analog front-end circuits. More importantly, the ability to print electronics at relatively low annealing temperatures makes it ideal for integration on flexible substrates.

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