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Analog and Mixed-Signal Circuits for Smart Sensors on Plastic Foils

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***Abstract*—Processes based on organic or metal-oxide semiconductors and able to manufacture electronics at near-to-ambient temperature are ideally suited for applications that require mechanical flexibility and ultra-low-cost. Examples include bendable displays, large-area sensor surfaces for man-machine interfaces, and smart sensors embedded in food packaging. The paper discusses key circuit blocks manufactured with low-temperature processes to enable sensor applications, like analog sensor frontends, digital to analog and analog to digital converters.**

I. INTRODUCTION

Silicon IC technology has been leading so far the market of electronics. Material performance and the maturity of the production process allow impressive electrical performance (speed, power-delay product, intrinsic gain, matching, etc.), enabling a multiplicity of different applications. However, when the level of performance required is lower, the ability to integrate electronics using new semiconductors on large and cheap substrates like plastic foils makes possible flexible and low-cost circuits, enabling a wealth of new applications: from flexible displays to large-area sensing surfaces, from sensors embedded in the packaging material of food and pharmaceuticals to disposable biosensors. These features can be achieved with novel low-temperature processes for the production of electronics which minimize the use of expensive vacuum-based steps and often exploit sheet-based or roll-to-roll approaches, sometimes even coupled to the use of additive patterning processes based on printing. Semiconductor materials suitable to low-temperature processing span both the range of organic compounds (and there we often speak of “organic electronics”) and the inorganic realm, where metal-oxide and even silicon-based approaches have been demonstrated.

At the beginning of the development of large-area low-temperature electronics, due to the difficulties in the integration of both n and p-type semiconductors, the technologies available were only unipolar, but still mature enough to enable plastic RFID tags [1] and microprocessors [2]. More recently, also complementary technologies have been demonstrated comprising evaporated [3] and printed [4] organic materials, or combinations of organic materials and metal-oxides [5]. Due to the intrinsic robustness of complementary circuits, in the future these technologies will surely overcome the unipolar ones, but nowadays these approaches still suffer from yield problems and unipolar technologies continue to be the most reliable for production.

Our research aims at demonstrating smart sensors that can be integrated on thin foils for packaging. These systems would comprise the actual sensor, analog data processing, a data converter and wireless transmission to a base station.

After a short introduction on the design environment that we set up to improve the effectiveness of our work in session II, some building blocks for smart sensors implemented using double-gate organic p-type thin film transistors (TFTs) are described in Section III. In Section IV we present a digital to analog converter implemented with n-type amorphous Gallium-Indium-Zinc-Oxide (aGIZO) TFTs. Some conclusions are drawn in Section V.

II. DESIGN ENVIRONMENT SETUP

In order to design circuits like sensor frontends, comparators and data converters, which are more complex than display backplanes, a good modeling of organic TFTs is mandatory. Models for organic TFTs and suitable design flows are normally unavailable in commercial CAD tools. For this reason we developed a complete design environment in house (Fig. 1) to provide the designer with a reliable analog transistor-level circuit simulator, assisted layout generation tools, LVS (Layout Vs. Schematic comparison) and DRC (Design Rules Checker) [6].

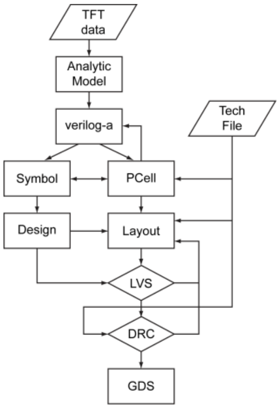

Figure 1. Flowchart of the design environment setup we implemented on commercial CAD software [6].

In order to model the DC currents of the TFTs that we exploit [7,8] for our circuits, we designed a full set of characterization structures, including transistors with different channel lengths, widths, and aspect ratios. From the data collected we derived the parameters required by our physical models of both organic and metal-oxide TFTs [9,10] to fit the measurements. The models we use are based on a variable range hopping (VRH) interpretation of the charge transport in the channel, which is typical for organic and disordered semiconductors. Under this assumption the carriers move thanks to thermally activated jumps from one localized energy state to another. The density of states (DOS) plays a fundamental role in the transport. Typically the DOS is assumed to be Gaussian, but often it can be approximated by a single exponential or by the sum of more exponentials. Following the same approach commonly used for MOSFETS, but considering the different carrier transport, we could express the channel current for a single exponential DOS as

$$I_c = \beta(V_G - V_S - V_T)^{\gamma} - \beta(V_G - V_D - V_T)^{\gamma} \qquad (1)$$

where β includes both geometrical and physical parameter and the factor γ, always larger than two, takes into account the variation of the mobility with the gate voltage. In case of DOS approximated by a sum of exponentials, the channel current can be expressed by a combination of currents similar to equation (1) [10]. The channel length modulation was modeled introducing a suitable V_D-dependence of the saturated current (Fig. 2) [9].

The models are simple, symmetrical and continuous: extremely important features for fast computation and reliable use in analog circuit simulators.

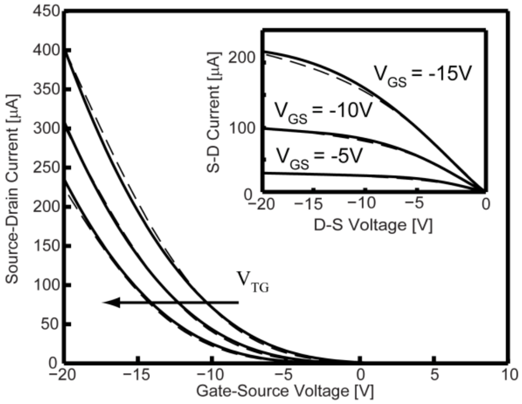

Figure 2. Measurements and model of the transfer and output (inset) characteristics of our organic p-type TFTs [11].

III. ORGANIC BUILDING BLOCKS FOR SMART SENSORS

The TFT model was described in a description language suitable for analog simulation and was used to design some building blocks for analog data processing and data conversion. A transconductor and a comparator have been designed exploiting a double-gate organic technology providing only p-type transistors.

A. Tunable Transcondutor

The signal coming from the sensor needs, before being converted into a digital value and sent to the base station, to be amplified and filtered in order to improve the signal-to-noise ratio (SNR). For this reason we designed a transconductor suitable for analog amplification and G_m - C filtering [9].

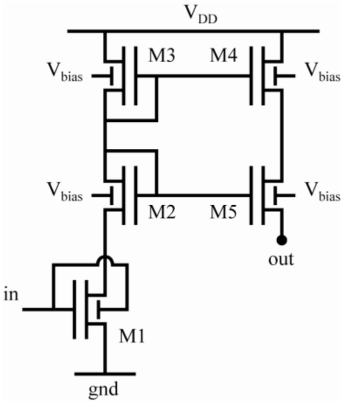

Figure 3. Schematic of the tunable transconductor suitable for analog amplification and filtering based on double-gate p-type organic TFTs [9].

The circuit (Fig. 3) adopts the organic TFT M2 in its saturation region as transconductor element, achieving in this way high linearity over a wide input range. The large output resistance provided by the 0Vgs connection guarantees a strong degeneration for the source-follower M1 which consequently buffers the input voltage on M2. It is worth noting that all the TFTs are p-type with positive threshold voltage: hence the channel is already conductive when gate and source are shorted together. The devices M3 and M4 create a current mirror that copies the current from the input branch into the output one. For an ideal current mirror the transconductance of the circuit results:

$$G_m \sim 1/r_{0,2} \qquad (2)$$

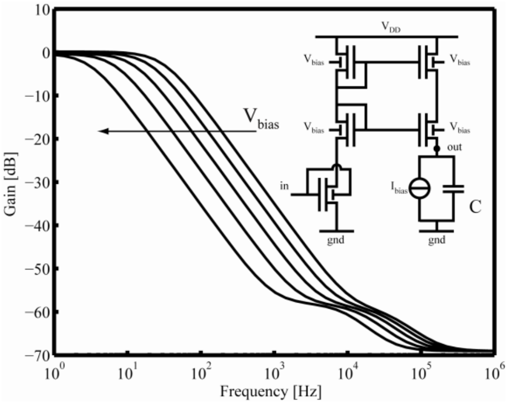

Figure 4. Bode magnitude plot of the filter shown in the inset (continuous line) simulated for different bias (V_{bias} = 0V, 5V, 10V, 15V, 20V) applied to the top gates [9].

Since both M3 and M4 do not work in saturation but in their linear region (due to the positive threshold), their V_{DS} is negligible, but the mirroring factor is smaller than one, hence the actual transconductance is smaller than the value given by (2).

The device M5 buffers the drain voltage of M3 on M4 keeping the mirroring factor closer to one and increases the output resistance of the circuit to ~$r_{0,5}$. The resulting open circuit voltage gain is:

$$G \sim T(r_{0,5}/r_{0,2}) \quad (3)$$

Where T<1 is the actual mirroring factor of the current mirror and $r_{0,x}$ is the output resistance of the TFT Mx.

The technology used for this design provides also a second gate (called "top gate" [7,9]) for the TFTs. This terminal shifts the threshold voltage of the TFT (Fig. 2), thus changing the transconductance and the Early voltage of the device. If we control together the top gates of M2, M3, M4 and M5, we can thus vary the transconductance of the circuit. The voltage gain remains constant since it is given by the ratio of two values which change in the same proportion when varying the top gate bias (equation 3).

If we use the transconductor in the G_m-C filter shown in Fig.4, the cut-off frequency occurs at

$$f_{-3dB} = 1/2\pi C r_{0,5} \quad (4)$$

and can be tuned by the top gate voltage through its influence on $r_{0,5}$ (Fig.4). Circuit measurements show that the transconductance can be tuned by one order of magnitude varying the bias within the supply rails, while keeping a good linearity (Fig. 5).

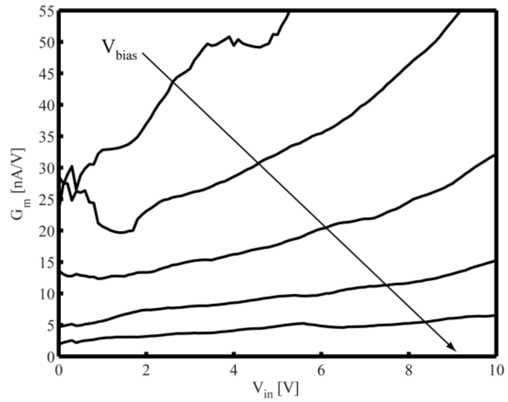

Figure 5. Measured transconductance for different bias (V_{bias} = 0V, 5V, 10V, 15V, 20V) applied to the top gates [9].

B. Latched Comparator

The sensor frontend amplifies and filters the analog signal in order to improve the SNR. Once the noise has been limited, the data can be sampled and converted to the digital domain using an analog to digital converter (ADC). One of the most important building blocks to build ADCs is the comparator, which can actually implement a one-bit quantization of the analog input amplitude. In order to achieve full output swing, high sensitivity and speed, we chose a latched topology which can achieve these requirements exploiting positive feedback [11].

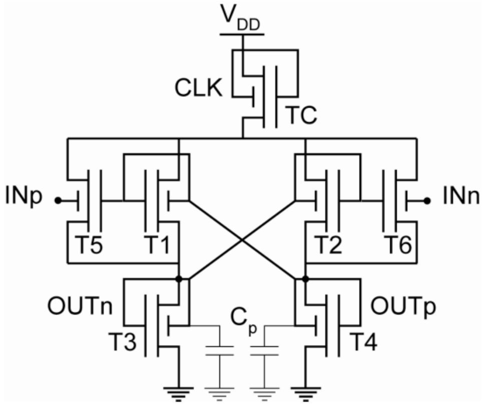

Figure 6. Schematic of the synchronous rail-to-rail latched comparator based on double-gate p-type organic TFTs [11].

The schematic of this design is shown in Fig. 6. This circuit implements a synchronous rail-to-rail latched comparator: the transistors pairs T1-T3 and T2-T4 are two inverters connected in a positive feedback configuration. When the clock signal goes low, the two outputs split either to the supply or to ground depending on the input imbalance provided to the top gates of the devices T5 and T6.

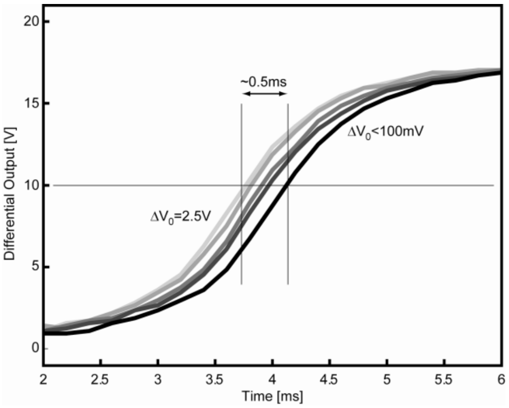

Figure 7. Measurement of the time needed by the latched comparator to perform a comparison. A differential input between 100mV and 2.5V is used [11].

In order to reach rail-to-rail output swing special solutions were exploited. The transistors T1 and T2 adopt a gate-top gate connection that improves the transconductance of the device and hence the gain of each inverter. The loads T3 and T4 use a 0Vgs configuration, which reduces at minimum the ohmic region in favor of the saturation one. The gain was measured larger than 46dB for a wide common mode input range, guaranteeing full output swing for differential inputs smaller than 100mV.

Unfortunately the pull down current provided by the load transistors in 0Vgs configuration is weak and the W/L of the loads needs to be large enough to bring the output nodes to ground. This affects the parasitic capacitance C_p which limits the intrinsic speed of the circuit. Feeding the input to the top gate of T5 and T6 makes a large decoupling capacitance unnecessary, avoiding a further slowdown of the comparison. Figure 7 shows the measured time required for the comparison when a differential input between 100mV and 2.5V is given to the comparator. For the smaller input, i.e. 100mV, the comparison takes place in ~4ms.

IV. METAL-OXIDE DIGITAL TO ANALOG CONVERTER

Metal-oxide semiconductors are another promising class of semiconductors for large-area flexible electronics. TFT made with these materials are typically n-type and can be processed at low temperature (T_{max}<250 °C). We made circuits using amorphous Gallium-Indium-Zinc-Oxide (aGIZO), which has a higher mobility (μ~20cm^2/Vs) than most other materials for low-temperature large-area electronics, and shows good local uniformity due to its amorphous nature.

With this technology, we designed a current steering Digital to Analog Converter (DAC) [8] that can be used even for video applications. The demands on speed and maximum current in this field are stringent, but the higher mobility and the better uniformity of GIZO TFTs were sufficient to design of a 6bit converter achieving a settling time <5µs and able to create the column data for a current programmed OLED display. The GIZO technology is n-type only, but the same design ideas could be easily ported to p-only platforms.

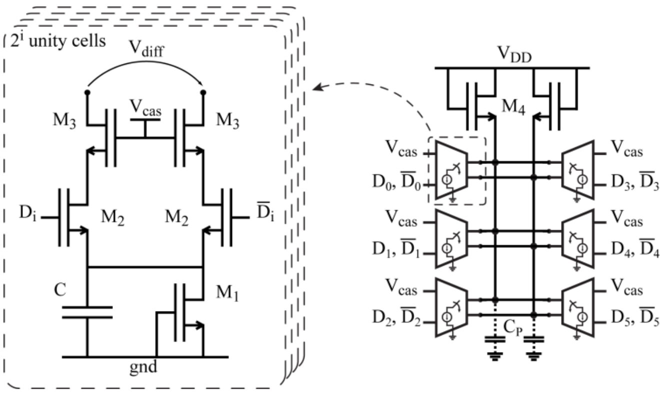

Figure 8. Schematic of the unity current cell (left) and connection of the 2^n-1 cells implementing the binary weighted current sources [8].

A DAC can also be used in analog to digital converters (ADCs), to generate the reference voltage that will be compared to the analog input in order to find its digital representation. The DAC is also the building block that typically determines the performance of the ADC in terms of linearity and speed.

State-of-the-art DACs manufactured with large-area technologies are based on amorphous silicon or LTPS (Low Temperature Poly Silicon) [12,13] TFTs, but exploit switched capacitor or resistive approaches to generate the output due to the poor matching of TFTs. Based on the information on the uniformity of our GIZO technology, we could design a 6b current steering DAC that showed a measured INL < 0.7LSB before calibration and a maximum sampling rate of 10MS/s.

In order to achieve the best result in terms of linearity, 63 identical unity cells were connected to obtain the weighted current sources. The schematic of the unity cell and their connection are shown in Fig. 8. The tail transistor M1 provides the actual unity current which is sent to the left or right load by the current switch (M2) according to the digital input. The devices M3 cascode the output and decouple it from the switching TFTs. In this work the DAC was not integrated with a current programming pixel engine for AMOLEDs; instead a diode connected load device (M4) was used to mimic it. Figure 9 shows the output spectra measured at a sampling rate of 1MS/s.

V. CONCLUSION

Large-area electronics on plastic foils open the doors to many applications that silicon IC technology cannot serve due to excessive cost and mechanical limitations. In this paper we demonstrated circuits suitable for smart sensor such as sensor frontends and latched comparators based on organic double-gate TFTs. We also demonstrated that metal-oxide TFTs, based for instance on aGIZO, can be exploited to build data converters even in application where more demanding speed constraints needs to be fulfilled, like displays working at video rate.

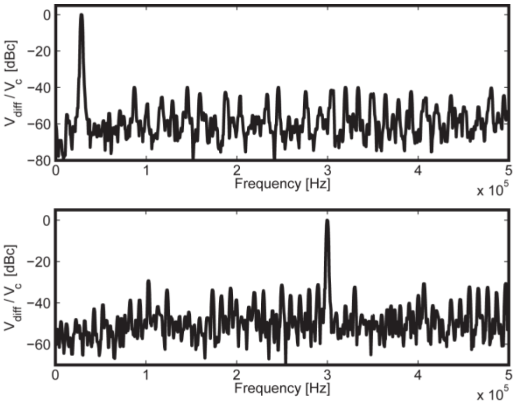

Figure 9. Measured output spectra for input sine at 30kHz and 300kHz for sampled at 1MS/s [8].

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