Organic Electronics 15 (2014) 904–912

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Letter

Variation-based design of an AM demodulator in a printed complementary organic technology

S. Abdinia [a,*], F. Torricelli [a,1], G. Maiellaro [b,2], R. Coppard [c], A. Daami [c], S. Jacob [c], L. Mariucci [d], G. Palmisano [b], E. Ragonese [b], F. Tramontana [e], A.H.M. van Roermund [a], E. Cantatore [a]

[a] *Eindhoven University of Technology, Department of Electrical Engineering, MSM, Eindhoven, The Netherlands*
[b] *University of Catania, DIEEI, Italy*
[c] *CEA-LITEN, Grenoble, France*
[d] *CNR-IMM, Rome, Italy*
[e] *STMicroelectronics, Catania, Italy*

ARTICLE INFO

Article history:
Received 27 August 2013
Received in revised form 27 January 2014
Accepted 28 January 2014
Available online 11 February 2014

Keywords:
Printed OTFTs
AM demodulator
Amplifiers
Envelope detector
Monte Carlo simulations
Parametric variations

ABSTRACT

In this work, the design of a high-frequency AM demodulator in a printed complementary organic technology is presented. The behaviour and the variability of printed circuits are predicted by means of accurate transistor modelling, statistical characterization, and Monte Carlo simulations. The effectiveness of the design approach is readily verified by comparing measurements and simulations of simple digital blocks as well as two differential amplifiers. These amplifiers can be used as continuous-time comparators in the demodulator. In addition, the possibility of high-frequency rectification using the printed organic TFTs is shown by providing the experimental results of an envelope detector measured under different load and input conditions. All the measurements are performed in air. Finally, the simulation of a complete AM demodulator system including the measured blocks is demonstrated.

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1. Introduction

Organic electronics is a promising field for the implementation of novel large-area applications on flexible substrates, including Radio Frequency Identification tags (RFIDs) [1,2], smart surface sensors [3], and actuators [4]. However, the relatively high variability in the characteristics of Organic Thin Film Transistors (OTFTs) makes it very challenging to have a robust design [5,6]. The global and local variations in the organic devices and the defects in the process lead to soft faults (deviation from the desired performance) and hard faults (failure to function) at the circuit level, respectively. Such shortcomings, which are a consequence of the chosen low-temperature and low-cost techniques, are seriously limiting the integration of organic circuits. In the case of unipolar technologies, the lack of n-type transistors further exacerbates the robustness issues. Although dual-gate transistors have been demonstrated to improve circuit robustness [7], the use of a complementary technology along with a design approach able to take into account the technology variability is the most promising route to further improve the complexity of both analogue and digital circuits [8,9].

The widespread use of organic electronics applications for a substantial improvement in the quality of everyday life could be fostered by the advancement of printing organic technology, due to its high throughput and potentially low cost [10,11]. However, the above-mentioned large variation of parameters in organic transistors becomes even more noticeable in printing technologies, due

* Corresponding author. Tel.: +31 402473407.
E-mail address: s.abdinia@tue.nl (S. Abdinia).
[1] Present address: University of Brescia, Department of Information Engineering, Brescia, Italy.
[2] Present address: STMicroelectronics, Catania, Italy.

http://dx.doi.org/10.1016/j.orgel.2014.01.021
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to the low degree of spatial correlation which is intrinsic in printing processes. That is why circuits implemented based on printed OTFTs [9–14] are mainly limited to digital electronics or large-area switch matrices.

Another important challenge for OTFTs is the high frequency (HF) performance and rectification efficiency needed by applications such as RFIDs. Indeed, working at frequencies above a few megahertz is very challenging for organic TFTs, since mobility typically does not exceed 0.5–1 $cm^2/V\,s$ [15,16]. Moreover, the typical high threshold voltage of OTFTs greatly impacts the rectifier Power Conversion Efficiency (PCE). State-of-the-art rectifying organic diodes adopt either vertical Schottky diodes [17] or diode-connected OTFTs [16]. The former provide the best performance in terms of operating frequency thanks to the very thin organic semiconductor layer. The latter are preferred when the rectifying diode has to be embedded in a complete RFID system, as it avoids specific technology steps and reuses the OTFTs. However, in this case diode performance is affected by the large channel length [16].

In this work, we present the design of a demodulator for amplitude-modulated (AM) radio signals, which is printed on a plastic substrate using a complementary organic technology. The circuit design and simulations are based on accurate modelling of p-type and n-type TFTs. Measurements of fundamental digital blocks such as inverters and NAND gates verify the model, and Monte Carlo (MC) simulations give an estimation of the effect of the technology parameter spread on circuit performance. The measured high frequency envelope detector and continuous-time comparators can be directly combined to make a demodulator operating at 13.56 MHz. The simulations of the complete AM demodulator system confirm its functionality and give suggestions for further improvements in the circuit design as well as in the OTFT modelling.

2. Modelling and simulations

2.1. OTFT model

The OTFTs are implemented in a top-gate bottom-contact structure, using a polytriarylamine (PTAA) derivative for p-type and an acene-based diimide for n-type semiconductors. The typical mobility of n-type and p-type OTFTs is 0.023 $cm^2/V\,s$ and 0.025 $cm^2/V\,s$, respectively. More details on the process can be found in [13].

The proposed OTFT model considers the static behaviour, the parasitic capacitances, and the parametric variability due to the printed technology. A physically based compact model [18] was used to fit the measured transfer and output characteristics of both p-type and n-type staggered transistors. The model takes into account the channel behaviour as well as the contact effects. According to the electrical measurements of long channel transistors, the drain current is a power law of the gate-source potential and the channel transport is modelled assuming an exponential distribution of traps in the semiconductor. Hence, when the transistor operates in accumulation (i.e., above threshold), the current expression reads [19,20].

$$I_D = \frac{W}{L}\left[G_t(V_A^{\gamma t} - V_B^{\gamma t})\left(1 + \frac{|V_{DS} - V_c|}{L \times E_p}\right) + \frac{V_{DS}}{R_{\text{off}}}\right] \quad (1)$$

where W and L are the channel width and length, respectively, G_t is a pre-factor dependent on physical and geometrical parameters (temperature, energetic disorder, charge spatial localization, and gate-insulator capacitance), γ_t is related to the disorder in the organic semiconductor, E_p takes into account the channel length modulation, and R_{off} considers the bulk current related to unintentional doping in the organic semiconductor.

When the transistor works in the sub-threshold regime, the measured drain current increases exponentially with the gate voltage. Such a behaviour could be attributed to deep trap states [21]. The above-threshold and the sub-threshold regimes are combined according to the interpolation function presented in [22]:

$$V_A = V_{ss}\ln\left[1 + \exp\left(\frac{V_{GS} - V_c - V_T}{V_{ss}}\right)\right] \quad (2)$$

$$V_B = V_{ss}\ln\left[1 + \exp\left(\frac{V_{GS} - V_{DS} - V_T}{V_{ss}}\right)\right] \quad (3)$$

where V_{SS} is the sub-threshold slope, V_C is the voltage drop at the source injecting contact, and V_T, V_{GS}, V_{DS} are the threshold voltage, the gate-source voltage, and the drain-source voltage, respectively.

Electrical characteristics of p-type OTFTs with a channel length ranging from 200 μm to 20 μm scale with the transistor channel length, and are accurately modelled with Eqs. (1)–(3). This suggests that the channel transport is the dominant physical mechanism. On the contrary, the electrical characteristics of n-type OTFTs do not scale with the transistor channel length. Indeed, the normalized drain current of a transistor with $L = 20$ μm is lower than that of a transistor with $L = 200$ μm. This experimental behaviour suggests that contact effects [23,24] are limiting the current. The contact resistance in these transistors is mainly related to the limited injection at the source contact induced by the presence of a reversed biased Schottky diode, the conductivity of which is strongly modulated by the gate bias. The current injected by the source contact as a function of the gate and drain potentials is modelled as in [25]:

$$I_c = WI_0\exp\left(4\sqrt{\frac{|V_c + V_c|}{2V_{00}}}\right)\left[1 - \exp\left(-\frac{V_c}{V_n}\right)\right] \quad (4)$$

where $I_0 = I_{00}\left(1 + \left(\frac{|V_{GS}| + V_{GS}}{2}\right)^{\gamma c}\right)$ and V_{00}, V_n, I_{00}, and γ_c are the contact parameters. The electrical characteristics of n-type OTFTs are modelled as the series of an "ideal transistor" and a reverse biased Schottky diode. Therefore, p- and n-type transistors have the same channel model, while only for n-type transistor is the contact resistance also needed.

Fig. 1(a) and (b) shows the measured (blue symbols) and modelled (red lines) characteristics of n-type and p-type transistors with dimensions (W/L) equal to $1000\mu/20\mu$. The transfer characteristics (left panels) are given for two different V_{DS}, 1 V and 40 V, and the output characteristics (right panels) are shown for three different V_{GS}, namely

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