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Transient TCAD simulation of three-stage organic ring oscillator

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Abstract It is demonstrated that drift-diffusion simulation is a powerful tool in design, optimization and verification of organic circuits. Starting from the simulation of single transistor structures, we treat inverter circuits with active load under both static and transient conditions while analyzing the effects of different transistor geometries. Never shown before, a dynamic finite element simulation of a full three-stage organic ring oscillator operating at 105 kHz is presented.

Keywords Organic electronics · OTFT · Simulation · Inverter · Oscillator

1 Introduction

Advances in fabrication techniques have resulted in organic thin film transistors (OTFT), which are increasingly interesting for electronic applications. The associated design of organic circuits creates the need for a solid modeling of device behavior.

Up to now, research has mainly targeted the analysis of static IV characteristics [1–4]. In the following, we report the simulation of dynamic OTFT behavior in inverter and oscillator circuits. The calculations are based on a finite elements drift-diffusion method distinguishing our work from SPICE-like approaches.

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2 Simulation environment

Our research is based on the commercial simulation suite SENTAURUS [5] that we modified to account for the special nature of organic semiconductors according to references [1, 2]. Input variables are device geometry, material specifications, and interface properties.

The simulator solves the drift-diffusion transport equations self consistently coupled to the Poisson equation. Details are given in [4]. We have implemented an effective Poole-Frenkel type mobility [2]. Typical values of $\chi = 2.5$ eV and $E_g = 2.5$ eV are chosen for the pentacene energy levels [3]. The effective density of states is set to 10^{21} cm^{-3} which equals the density of molecules in pentacene films [2, 3]. A work function of 4.9 eV is used to model the gold drain and source contacts.

3 OTFT simulation

Simulations of OTFT output and transfer characteristics have already been demonstrated in the literature [1–4]. Fitting experimental IV data supplies valuable knowledge about physical device parameters such as fixed interface charges and traps [3, 4]. Typical values are reported in [4] with a trap concentration of $N_t = 1 \cdot 10^{12}$ cm^{-2} at a level 0.15 eV above the valence band.

We have fabricated and measured pentacene OTFTs with a channel length of $L = 20$ μm and a width of $W = 10$ μm. The devices are prepared in bottom contact configuration on heavily n-doped Silicon wafers covered by a 200 nm thick SiO_2 oxide ($C_{ox} = 1.8 \cdot 10^{-8}$ Fcm^{-2}). Measured and simulated output characteristics are both displayed in Fig. 1. The device has an excellent mobility in the order of $\mu = 2$ cm^2/Vs. The simulation extracts positive fixed interface charges

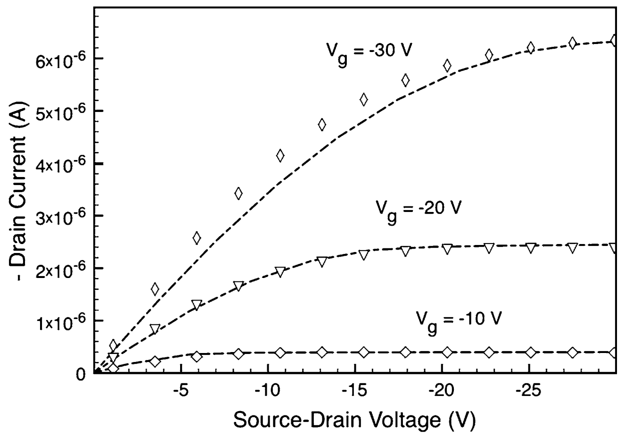

Fig. 1 Experimental (symbols) and simulated (lines) output characteristics of pentacene OTFT with $L = 20\ \mu$m

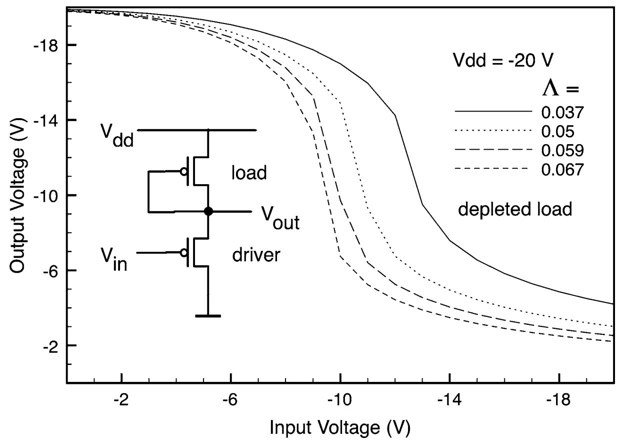

Fig. 2 Influence of the geometry factor Λ on voltage transfer characteristic of an organic inverter with depleted load

with $Q_\mathrm{f} = 1 \cdot 10^{11}$ cm^{-2} and acceptor-type traps of density $8 \cdot 10^{11}$ cm^{-2} at a level 0.16 eV above the valence band.

4 Organic inverter circuits

Based on the pentacene transistor shown in the previous section, we have realized simulations of inverters. A main restriction in the design of organic electronics results from the limitation to p-type transistors. Although research aims at n-type devices [6], materials and fabrication are still immature. Therefore, it is of great interest to design exclusively p-based circuits for digital and analog purposes. The inset in Fig. 2 shows a possible inverter layout with depleted load.

A main advantage of MOSFET based designs is that they can easily be tuned by changing the $\lambda = W/L$ ratios of the transistors. Figure 2 demonstrates the strong influence of the geometry factor

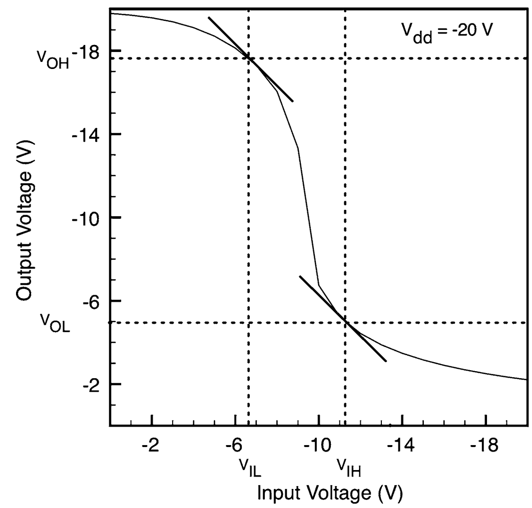

Fig. 3 Simulated voltage transfer characteristic of organic inverter with depleted load ($\Lambda = 0.059$), gain of 4.6 and static noise margin of $NM_\mathrm{L} = V_\mathrm{IL} - V_\mathrm{OL} = -1.6$ V, $NM_\mathrm{H} = V_\mathrm{OH} - V_\mathrm{IH} = -6.4$ V

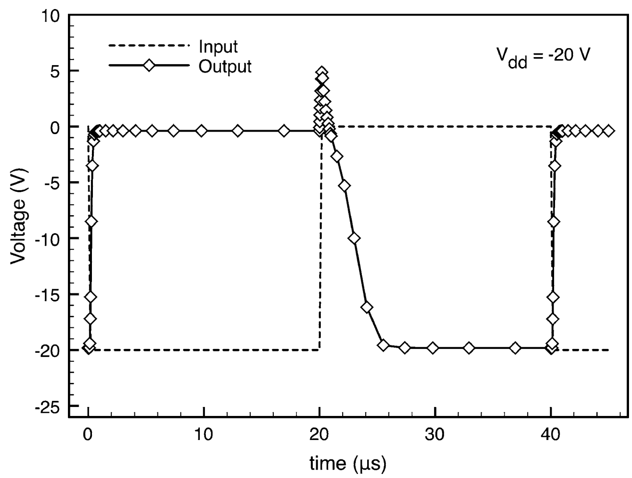

Fig. 4 Simulated transient response of inverter with depleted load ($\Lambda = 0.059$) and a load capacity $C_\mathrm{L} = 20$ fF connected to V_out

$$\Lambda = \frac{\lambda_{driver}}{\lambda_{load}} = \frac{W_{driver} \cdot L_{load}}{L_{driver} \cdot W_{load}} \tag{1}$$

on the voltage transfer characteristic of the inverter. Optimizing the symmetry of the input and output voltage curve to -10 V leads to a value of $\Lambda = 0.059$. The optimized characteristic is presented in Fig. 3. It has a gain of 4.6 and a static noise margin of $N_\mathrm{ML} = V_\mathrm{IL} - V_\mathrm{OL} = -1.6$ V and $N_\mathrm{MH} = V_\mathrm{OH} - V_\mathrm{IH} = -6.4$ V, respectively.

Simulations of level shifters and more complex logic gates have been performed in the same manner, but are not subject of this contribution.

To determine the switching behavior, we simulated the inverter circuit connected to a load capacity $C_\mathrm{L} = 20$ fF. The results are plotted in Fig. 4. The output voltage shows distinct asymmetry for rising and falling edges. The rise time going from 0 to −20 V is approximately 5 μs, while the fall time is close to 0.5 μs.

This asymmetry is a characteristic feature of inverters with depleted load and is also observed experimentally [6]. During the state $V_{in} = 0$ V, the load capacitance C_L is fully charged and $V_{out} = -20$ V. Changing the input to −20 V instantly opens the driver OTFT. The resulting current discharges the capacitance. When closing the driver OTFT with $V_{in} = 0$ V, C_L needs to be recharged to obtain the desired output level of −20 V. For the charging process, current must flow through the load transistor the gate of which is still at 0 V. Therefore its impedance is initially high and the charging relatively slow. As demonstrated by the simulations, driving the output to −20 V is consequently faster than shifting it the opposite direction.

At present, research in the field of organic electronics is primarily devoted to the optimization of device behavior, materials and fabrication processes. Attention gradually shifts to the realization of circuit applications. Rise and fall times determine the maximum switching speeds of digital circuits so that their tuning is a typical optimization task. The presented TCAD framework for organic circuits will likely be the tool of choice for future circuit designs.

5 Simulation of organic ring oscillators

The realization of ring oscillators has been a key milestone and the proof that large integrated organic circuits are feasible [8–10]. For logic applications, it is not sufficient to simply build inverters. It is required that they amplify the input signal so that the signal is not lost after a number of logic gates. Furthermore the output of one logic gate must be able to drive the input of another gate. This requires that input and output voltage ranges match.

A ring oscillator consists of an odd number of inverter stages. The output of one stage is connected to the next stage. The last inverter connects to the input of the first one closing the ring. The odd number of inverters prevents the system to obtain a stable operation point. For oscillation to take place, the previously mentioned requirements must strictly be obeyed by each inverter stage. Ring oscillators running at frequencies of upto 220 kHz have been reported in the literature [10].

To test the capabilities of our simulation approach, we have set up a three-stage ring oscillator using the optimized inverter treated in the previous section. The overall circuit is shown in Fig. 5. We again included a load capacitance $C_i = 20$ fF in each stage to explicitly account for parasitics.

To start the oscillation, the supply voltage V_{dd} is ramped to −20 V during the first 0.5 μs of the simulation. The node voltages at each inverter stage during startup are given in Fig. 6. After the initial V_{dd} ramp, the oscillator successfully reaches steady-state operation (Fig. 7). The simulated oscillation frequency equals 105 kHz (delay time = 3.16 μs) and strongly depends on the magnitude of the load capacitances C_i.

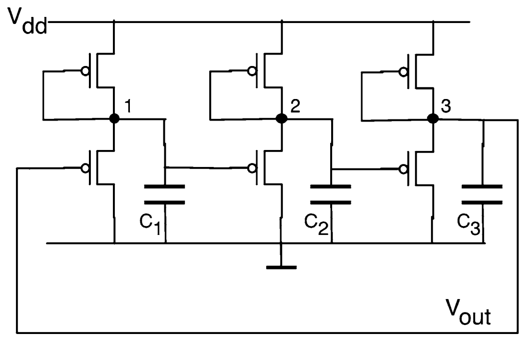

Fig. 5 Schematics of a three-stage organic oscillator. Load capacitances have been included in the simulations at each output node to account for parasitics

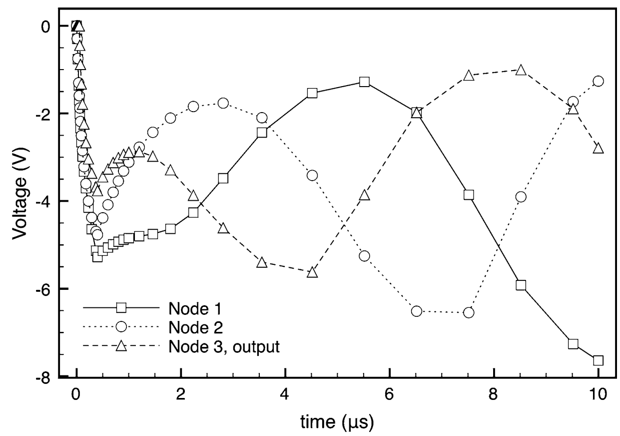

Fig. 6 Transient startup of oscillator circuit. V_{dd} is ramped to −20 V during the first 0.5 μs

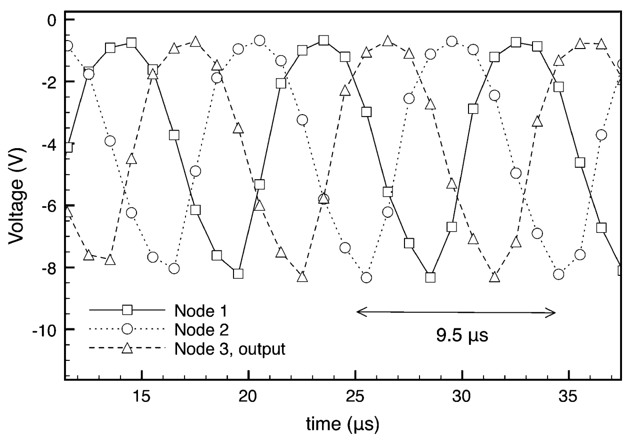

Fig. 7 Steady-state operation of simulated three-stage organic oscillator with $V_{dd} = -20$ V

6 Outlook

A seamless simulation flow from single organic transistors to inverters and complex oscillator circuits has been presented. Based on measurement and characterization of OTFTs, the TCAD approach projects a maximum of physical device modeling into circuit simulations. This is of particular importance in organic electronics, since each material combination, fabrication process etc. results in different device properties. In this context, standard circuit models are only suitable to a very limited extent. The authors believe that the presented workflow will become standard in design and optimization of organic circuit applications.

7 Conclusion

We have reported the simulation of organic thin film transistors, inverter circuits and oscillators employing the software tool SENTAURUS. The modeling and simulation of single organic transistors is the basis to predict static and transient behavior of inverters. Multiple inverter stages have successfully been joined to demonstrate, to our knowledge for the first time, a finite elements simulation of a complete organic ring oscillator. This shows that simultaneous drift-diffusion simulations of six OTFTs connected in a circuit are feasible. In conclusion, the presented method is suited to give insight in the operation of organic circuits optimizing future design processes.

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