Fast polymer integrated circuits based on a polyfluorene derivative

W. Fix, A. Ullmann, J. Ficker, H. Rost, W. Clemens
Siemens AG, CT MM 1, Germany
walter.fix@erls.siemens.de

D. Brennan, D. Welsh, J. O'Brien,
The Dow Chemical Company
jobrien@dow.com

Abstract

Low-cost fabrication of integrated circuits on flexible substrates is best realised by using semiconducting and insulating polymers from solution. We report on a novel concept based on p-type organic transistors only. A poly(fluorene bithiophene) derivative is used as active semiconducting layer, a copolymer blend as insulator, a flexible polyester film as substrate and metal electrodes. To enable vertical interconnects, the insulating layer is patterned.

Polymer FETs (PFET) with a mobility of 0.015 cm^2/Vs and an on/off ratio above 10^6 are presented as well as ring oscillators with frequencies of 10 kHz and propagation stage delays of 10 µs.

These results clearly indicate, that integrated plastic circuits (IPC) based on soluble polymer semiconductors and processed on flexible films are very suitable for inexpensive high volume electronic applications.

1. Introduction

The relevance of organic field effect transistors (OFETs) has increased exceptionally in recent years. While a number of concepts exist for OFETs [1], only a few have resulted in integrated circuits (ICs). The performance of a ring oscillator circuit gives a good benchmark to compare the efficiency of the different realization methods. Complementary circuits based on a combination of organic and inorganic semiconducting materials showed ring oscillator frequencies up to 20 kHz [2]. Different concepts using small molecules as semiconductor give frequencies in the range of several kHz [3,4] and up to 900 kHz [5].

All these concepts are based on complex and expensive production processes. Using polymer solutions as semiconductor give the possibility of reaching very low production costs.

The performance of polymer ICs in recent years has been rather low [6]. However, higher performance can, in principle, be realized. This view is supported by the increased ring oscillator frequency reported in the latest publications [4,7,8].

The economical realization of the polymer materials results not only from the solubility of the semiconductor and the insulator, but also from a simple setup and the inexpensive production process. This setup is based on top gate polymer FETs (PFETs) with only p-type semiconductor on a polymer substrate.

2. Device fabrication

A flexible polyester film is used as a substrate, thereon the gold source/drain electrodes are patterned with standard photolithography. Channel lengths from 2 to 50 µm and widths from 1 to 10 mm are realized. The semiconducting polymer, a p-type poly(fluorene bithiophene) derivative (Fig. 1) [9], is dissolved in chloroform and applied by means of spin coating resulting in a 30 nm thick layer.

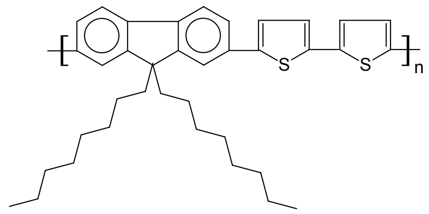

Figure 1. Poly(fluorene bithiophene) derivative

As an insulating layer, a copolymer blend with a dielectric constant of 2.5 is dissolved in dioxane and spin coated on top of the semiconducting layer. This results in a homogeneous 200 nm thick layer without any pinholes.

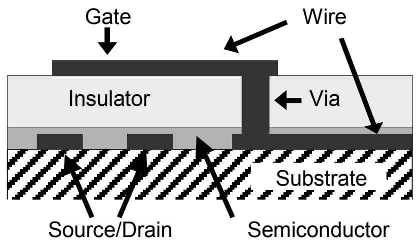

Figure 2. OFET cross-section with via

Low-ohmic vertical interconnects (vias) are indispensable for integrated circuits. To enable vias, holes through the insulating and the semiconducting layers are realized by photolithography and a dissolving process. The transistors and the vias are completed with the deposition and patterning of the gold gate electrodes.

The vias have a negligible resistance (<3 Ohm). Figure 2 shows a cross-sectional view of a top gate PFET and a vertical interconnect. All processing steps are performed under cleanroom conditions in presence of oxygen and humidity.

3. Results

Electrical measurements on single PFETs show a good current saturation with a high on/off ratio of 10^6 and a neglectable hysteresis. Figure 3 shows the output characteristics of a PFET with a channel length of L = 10 µm and width of W = 10 mm. The delayed rise of the current at a drain voltage of about -2V is mainly due to the small mismatch between the work function of the source/drain electrodes and the highest occupied molecular orbital (HOMO) of the semiconducting material.

From the transfer characteristics, a threshold voltage of -3,5 V is derived (Fig. 4). Using the standard method [7,10], we obtained a charge carrier mobility of about 0.015 cm^2/Vs in the saturation regime (Fig. 5).

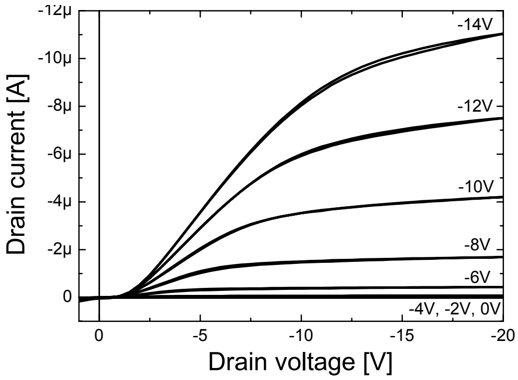

Figure 3. PFET output characteristics

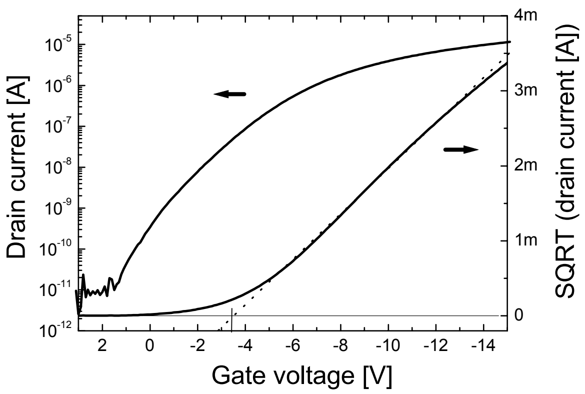

Figure 4. PFET transfer characteristics (SD=-20V)

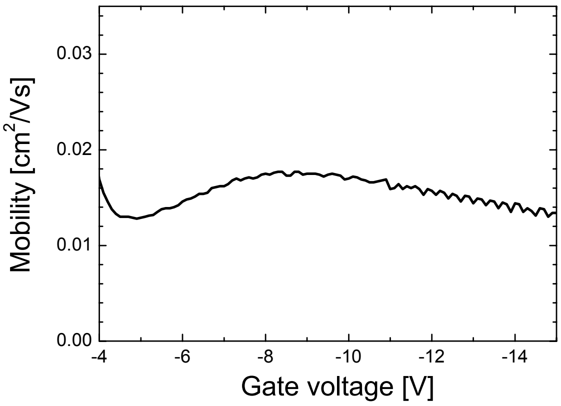

Figure 5. Mobility vs. gate voltage

By combining two PFETs with different channel geometries (load PFET: L = 10 µm, W = 1 mm, drive PFET: L = 10 µm, W = 5 mm) a simple inverter is realized. Fig. 6 shows the output voltage versus the input voltage with a very small hysteresis and a gain of about 2 (V_{supply} = -25 V).

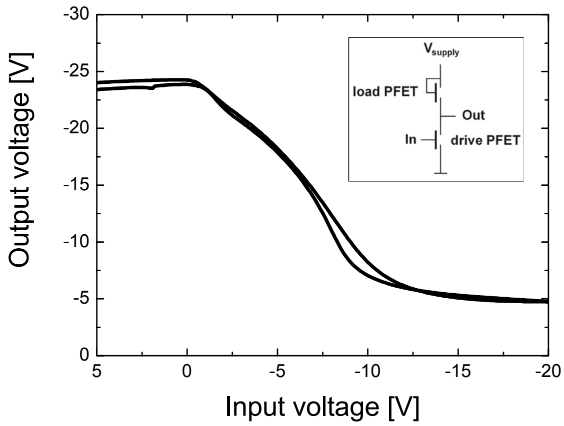

Figure 6. Inverter characteristics

The performance of integrated circuits is demonstrated by the results of a 5 stage ring oscillator. Each inverter stage consists of a load PFET with L = 5 µm, W = 2 mm and a drive PFET with L = 2 µm, W = 5 mm. The output of the last stage is connected to the input of the first stage and to the gate of an output OFET, which has the same channel geometry as the drive OFET (Fig. 7).

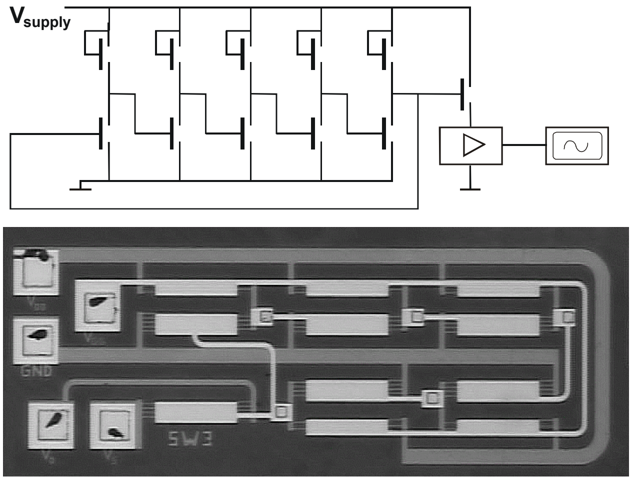

Figure 7. Measurement circuit layout and top view of a 5 stage ring oscillator

The layout of the ring oscillator allows us to apply a voltage to the gate electrodes of all load PFETs independent of the supply voltage. For typical measurements both voltages are the same. To measure the ring oscillator frequency, the channel of the output transistor is connected in series with a fast current amplifier and a common voltage of -15 V is applied. The ring oscillator starts oscillating if the supply voltage reaches a certain value, which depends on circuit design, PFET threshold voltage and on/off ratio. With the layout mentioned above, the onset voltage was about -15 V and with a voltage of -25 V a frequency of 10.4 kHz was reached (Fig. 8). This is equivalent to a stage delay of 9.6 µs.

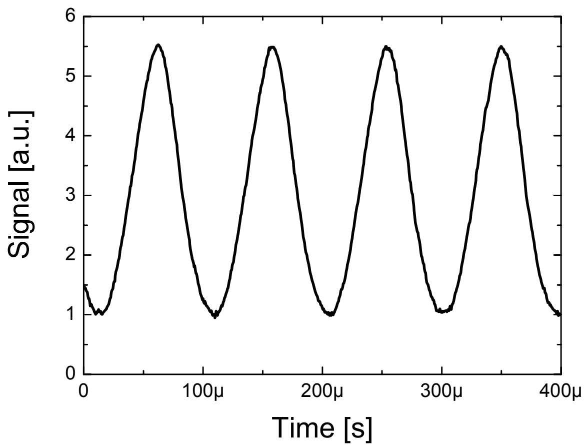

Figure 8. Frequency of 10.4kHz of a 5 stage ring oscillator

The ring oscillator frequency is limited by the charging and discharging time of the capacitive load of a stage output, which is the sum of the input capacitance of the following stage and a parasitic capacitance. The charge and discharge currents are limited by the channel conductivity of the load PFET and drive PFET, respectively and by series resistances, e.g. contact resistance between electrodes and semiconductor. Thus, not only the mobility is crucial, but also parasitic capacitances and series resistances which result from the PFET design and the circuit layout are of special importance.

The simplicity of the setup requires a good chemical stability of the semiconducting material, for which polyfluorene is well-known. A further requirement for electronic circuits is constant operation over time. For more than 250 hours such a ring oscillator circuit was constantly run. During the operation a dependence on the surrounding illumination was detected.

4. Conclusions

In summary we presented a concept for fast p-MOS type integrated circuits based on soluble organic polymers. All involved layers consist of polymers, except the electrodes. As active semiconductor a poly(fluorene bithiophene) derivative is used. High performance polymer ring oscillators with a stage delay of 9.6 µs and a frequency of 10.4 kHz could be reached with this simple setup.

We are convinced that polymer electronic has the potential to enable applications like contactless identification tags as electronic barcodes or driving circuits for large scale organic displays. However, a precondition is that the processing of organic electronic is much simpler than silicon electronic processing. For that reason, inexpensive techniques such as printing in a reel-to-reel process are necessary, which are only possible with soluble materials.

We are glad to acknowledge the support of G. Döhler and W. Glauert for useful discussions (both University of Erlangen).

5. References

[1] IBM J. Res. & Dev., **45,** No. 1 (2001).

[2] C. D. Sheraw et al., Intern. Electron. Device Meeting, 25.4, 619 (2000).

[3] D. J. Gundlach et al, submitted to Intern. Electron. Device Meeting (2001).

[4] G.H. Gelinck, T.C.T. Geuns, D.M. de Leeuw, Appl. Phys. Lett., 77, 1487 (2000).

[5] J. H. Schön, Ch.Kloc, Appl. Phys. Lett., **79**, 4043 (2001).

[6] A. R. Brown, A. Pomp, C. M. Hart, D. M. de Leeuw, Science, **270**, 972 (1995).

[7] A. Ullmann et al., Mat. Res. Soc. Symp. Proc., 665, C7.5 (2001).

[8] J. Ficker, A. Ullmann, W. Fix, H. Rost, W. Clemens, in press Proc. of the SPIE, 4466 (2001).

[9] M. T. Bernius, E. P. Woo, Dow Chemical Company, US Patent No.: US 6,204,515 B1 (2001).

[10] S. M. Sze, Physics of Semiconductor Devices, (J. Wiley & Sons, New York, 1981).