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# Ring oscillator fabricated completely by means of mass-printing technologies

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**Abstract**

We report on the first successful fabrication of an integrated circuit solely by means of fast, continuous mass-printing technology. Our demonstration object is a seven-stage ring oscillator which delivers an ac-signal with a frequency of approximately 4 Hz. The process speed of the order of 1 m/s demonstrates the high potential of mass-printing techniques for the production of low-cost electronics. By identifying major technological issues that occur upon printing of electronic circuits, routes for further development are clarified.



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## 1. Introduction

During the last years, research has increasingly concentrated on the processing of functional polymers for the development of electronic devices. Researchers hope to realize extremely cost-effective applications on flexible substrates, such as plastic foils or paper in the future, in order to equip and embellish many daily life products as "smart objects". Among other functions, it is primarily electronic circuits based on organic field effect transistors (oFETs) that are of interest. In the last years, a great number of methods for the processing of

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material layers necessary for oFET circuits have been proposed which are frequently borrowed from traditional electronics production (e.g. Refs. [1–10]).

However, the solubility and dispersibility of functional polymers in various solvents suggest applying them as formulated inks which can be deposited into patterned layers by means of printing techniques. Some research groups have adapted methods from printed circuit board production, such as screen printing and pad printing [11–14], while many other groups have used inkjet printing [15–18]. By combining these methods in different ways, it has been possible in the past to show that comparatively complex circuits based on organic semiconductors with hundreds [7] or even thousands [19] of transistors are possible and that microsecond switching speeds can be achieved [11,20]. Furthermore, there are ring oscillator circuits for which exclusively polymer materials were used [1,9,11,12,15], not only for the semiconductor but also for the conductive source/drain and gate electrodes as well as for the gate dielectric. Completely printed single transistors and ring oscillators produced by pad printing [11,12] and inkjet [15–17] have been reported.

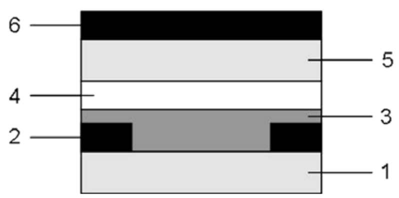
Compared to the approaches mentioned so far, mass-printing technologies bring very special challenges. The traditional technologies of offset, gravure and flexographic printing are currently primarily used for the production of newspapers, books, packaging etc. and have a $10^3$–$10^6$ times higher productivity than other printing methods [21]. Typical printing speeds range from 2 m/s to 15 m/s. With respect to a future mass production of polymer electronics, it is a key issue to use solely these mass-printing methods for a successive deposition of different layers. So far, these printing methods as well as the necessary printing machines have only been optimized for visual image properties. Printing materials with electronic functions imposes more stringent requirements on the methods, machines as well as ink chemistry and rheology [22], which go beyond the current state of today's printing technologies.

## 2. Experimental

While the preparation of oFETs from solution has already become a routine technique [15], the actual deposition of thin semiconductive or dielectric layers by means of additive printing methods still remains challenging. We therefore believe that the key task in printed electronics is represented by the transfer of processing steps from the laboratory using solution deposition techniques like spin coating and casting to the printing machine. A ring oscillator consisting of several inverter stages is considered to be a useful example of testing logic capability in integrated circuits [12]. By presenting a fully printed oscillator the general concept of printed electronics can be proven. Furthermore, potential risks and bottlenecks of the approach can be identified.

Fig. 1 shows the setup of our oFETs together with the used materials and printing methods. An oFET top gate architecture was chosen primarily because the first deposition step of source and drain contacts requires the highest resolution and can be accomplished most easily on a plain and defined substrate like a smooth polyester foil (PET) rather than on a printed multilayer surface with significant roughness. Our substrate is a commercially available (Dupont Tejin) PET foil with a surface roughness of 8 nm. In order to assure dimensional stability the foil is pre-shrunk by means of thermal and mechanical stress. The foil is subject to a standard in-line corona treatment before the source/drain structures are offset-printed on top of it.

The channel length of the transistor representing the distance between source and drain electrodes was set to $L = 0.1$ mm, and the channel width $W = 30$ mm and $W = 6$ mm for the load and driver transistors, respectively. However, no attempts were made so far to further reduce the channel length so as to obtain a significantly increased inverter




| layer | material | method |
|---|---|---|
| 1 substrate | PET | - |
| 2 source/drain | PEDOT:PSS | offset |
| 3 semiconductor | F8T2 | gravure |
| 4 low-k dielectric | BuS* | gravure |
| 5 high-k dielectric | Luxprint | flexo |
| 6 gate | Ag-ink | flexo |

Fig. 1. Layer setup of the printed oFETs together with the used materials and printing methods, respectively (* BuS: butadiene–styrene-copolymer).