All-printed electronics and its applications: a status report

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Abstract

Mass printing technologies are promising technologies for the production of inexpensive electronics.

In recent experiments, we have fabricated an integrated circuit solely by means of fast mass-printing methods without any steps breaking the production continuity. Our results clarified important issues that have to be taken into account when adapting printing technologies to the fabrication of electronics. Compatibility of materials and processes for the deposition of different layers on top of each other, uniformity and quality of layers with respect to electronic requirements as well as resolution and registration turned out to be challenging for the adaptation of printing technologies.

In addition, first applications are already available, which rely on simplicity and inexpensive fabrication instead of high integration and high-end performance. Flexible cardboard-keyboards, chipless paper-identification systems as well as simple sensor systems can be regarded as applications that are paving the way for more sophisticated, printed electronics applications.

Introduction

The interest in printed electronics has significantly increased in recent years. Many applications, like radio frequency identification tags (RFID) [1,2] and organic displays [3], have been identified that would notably benefit from the cheaper production costs that can be achieved by means of printing technologies. Especially mass printing technologies like offset, gravure and flexographic printing offer a great potential for cheaper production compared to traditional lithographic and vacuum evaporation processes used in silicon-based industry. An additional advantage of plastic electronics is the fact that very large areas can be printed on flexible substrates. This allows for completely new applications and markets compared to silicon-based industry which is largely restricted to rigid substrates.

Organic materials, especially polymers, seem to be most promising candidates for the application with printing technologies. Since the discovery of the first conductive organic materials in the 1970's, big research efforts have been made in order to improve the properties of these materials in terms of conductivity, mobility or processability. These days, the first organic functional materials are leaving the laboratory research level and the competition for the first "real" application has started.

An important issue for the use of organic materials in electronics applications is, apart from the resolution, the charge carrier mobility, which determines important parameters of electronic devices such as the switching speed. Although the mobility of inorganic materials is much higher than the mobility of organic materials, there are first organic semiconductors which exceed the mobility of amorphous silicon of 1cm²/Vs. However, these organic materials are usually small molecules. The small molecules with the best mobilities, like pentacene or rubrene, have the disadvantage of a very poor solubility. These materials are, thus, not suited for usage in solution-based processes like printing. Therefore, these materials can only be processed in cost-intensive vacuum evaporation processes. On the other hand, there are polymers which have a good solubility, but usually lower mobilities compared to the best small molecule semiconductors. Big research effort has been made in order to improve the polymeric semiconductors so that first polymers with a mobility in the range of 0,1 to 1 cm²/Vs are available now.

Most of the inorganic integrated circuits are made by integration of p and n-conducting areas within one device. This so called CMOS technology has the advantage of enabling fast switching and low power consuming devices. In case of organic materials it is much more difficult to implement such a complementary technology. Usually the properties of n-conducting organic materials are somewhat behind comparable p-conducting materials because of intrinsic chemical issues of charge transport and stability [4]. However, within the last years big improvements with regard to the behaviour of these materials have been demonstrated on laboratory scale, so that there are a number of n-type organic semiconductors available now. Even devices with properties that can be influenced by the choice of the dielectric, the electrodes or by modifications of the chemical structure of the organic semiconductor from n-type to ambipolar up to p-type behaviour have been demonstrated [5,6].

Apart from the fact of having an appropriate semiconductor, it is also important to have a suitable dielectric. For the microelectronic revolution the insulator - SiO_2 - was as important as silicon itself. For organic semiconductors it is not possible to create the insulator simply by oxidizing the semiconductor as in case of silicon. Although there is a wide range of dielectrics available, both organic and inorganic, the interplay of the semiconductor and the insulator, especially at the interface, remains a challenging issue. Veres et al. [7] showed that, in contrast to the conventional wisdom, a high dielectric constant, ensuring a high capacitance, is not always the best choice. High dielectric constant materials are very polar and therefore inducing disorder at the semiconductor / insulator interface. This leads to a reduced field effect mobility. Low k materials are unpolar. Thus, transistors with low k dielectrics show higher field effect mobility than transistors with high k dielectrics. Therefore, the increase in mobility compensates for the loss in capacitance through the lower dielectric constant.

For the conducting parts of the circuits, like electrodes and interconnections, some polymers, as Polyanilin (PAni) and poly(3,4-ethylenedioxythiophene) doped with poly(styrene-sulfonate) (PEDOT:PSS), as well as metal particle filled inks (e.g. silver inks) are commercially available. The polymeric conductors have the disadvantage of a relatively low conductivity compared to metallic conductors, whereas metal filled inks have problems regarding material costs.

The key advantage of polymer electronics is their ability to be processed from solution-based processes like printing. Printing processes, especially mass printing like offset, gravure or flexographic printing, allow for a more cost–efficient production compared to traditional production of silicon-based electronics by means of lithographic and high vacuum processes.

Since the discovery of printing, however, the development has concentrated on the optimization of the printing product for the requirements of the human eye. An overview of the requirements of traditional printing and printing electronics is presented in table 1. In order to fulfil the requirements of printed electronics, much higher standards have to be considered. The resolution and the registration have to be much higher for printed electronics compared to traditional printing in order to fulfil the industrial standards in terms of switching speed. As for printed electronics only the electronic properties are important and not the visual output, completely new parameters are becoming important. For example the choice of the solvent becomes a critical issue. It has to be taken into account that underlying layers are not dissolved during subsequent overprinting. There are also experiments which demonstrate that the quality of the deposited layer can be influenced by the choice of the solvent [8]. In the case of printing for visual output layer homogeneity and layer thickness are only important in order to have a clear, not interrupted picture. For electronic applications layer thickness and especially the homogeneity are of crucial importance for the functionality of the device.

requirement	traditional	electronics
resolution	> 20 µm	<< 20 µm
register	± 5 µm	< 5 µm
edge sharpness	high	very high
layer thickness	~ 1 µm	30 … 300 nm
homogeneity	not important	very important
adhesion of layers	important	important
solvents of inks	cost issue	functional issue
purity of solutions	not important	very important
visual properties	very important	not important
electronic properties	not important	very important

Tab. 1. Comparison of requirements for traditional printing for visual output and for printing of electronics.

One driving force for the development of printed electronics is the printing of radio frequency identification tags (RFID-tags). By means of theses tags information can be transmitted contactless via radio frequency signals. Such a RFID-tag consists of a chip and an antenna. For the antenna mainly metal particle filled inks are used. Polymer materials do not have sufficient conductivities to meet the requirements of the standard frequencies for RFID at 125kHz and 13,56 MHz. Today, antennas are usually produced by means of screen or inkjet printing of metal, mainly silver, particle containing inks [9,10]. As these technologies suffer from low cost efficiency compared to mass printing some groups have tried to implement flexographic printing for the fabrication of antennas.

Printing of RFID-tags allows for the application of this technology in areas where the currently produced tags are too expensive. Possible applications are the replacement of optical barcodes in supermarkets, the tracing of products in logistic systems, access tickets or luggage labelling.

Some groups have already reported on organics-based integrated circuits with increasing complexity. These circuits have been produced by non-continuous processes like doctor blading or pad printing. In 2005, PolyIC presented a polymer-based RFID-tag working at 13,56 MHz, but did not report on the related production process [11]. In February 2006, Philips showed a RFID tag based on plastic electronics working at 13,56 MHz [12].

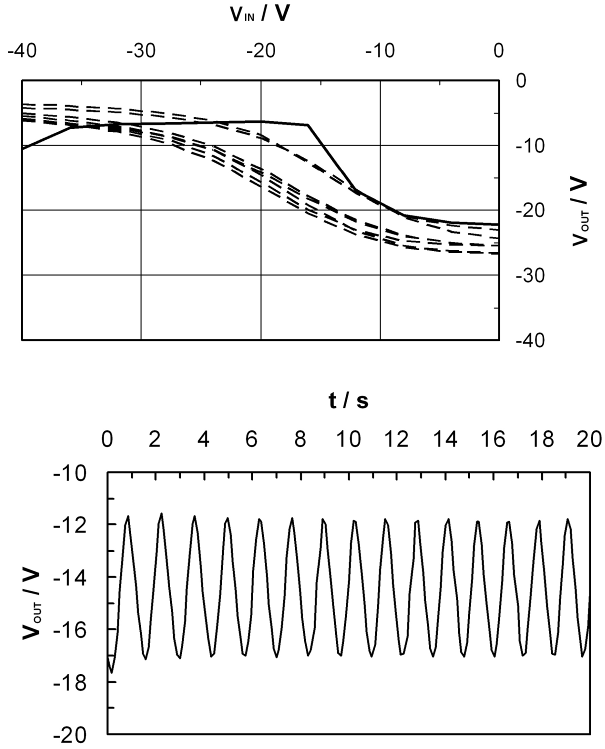

Fig. 1. Static transfer curves of individual inverter stages of a printed circuit (dashed lines) and of seven inverter stages connected in series (solid line).

Dynamic output signal of a printed ring oscillator at a supply voltage V_{DD} = -40 V.

These results demonstrate the capability of organic electronics for its use in applications like RFID-tags. However, in order to fulfil the requirements in terms of production costs the processes used for the above mentioned tags are not appropriate. Therefore, mass printing technologies have been adapted for producing organic electronics. These technologies are very efficient and allow for a very inexpensive production.

In order to demonstrate the capability of mass printing technologies for the production of integrated circuits, we have successfully produced a simple 7-stage ring oscillator in cooperation with BASF and Lucent Technologies. The ring oscillator consists of offset printed source/drain structures offset printed from an inhouse re-formulation of poly(3,4-ethylenedioxythiophene) doped with poly(styrene-sulfonate) (PEDOT:PSS) in a water-based dispersion (Baytron P®) onto a poly(ethylene)-foil (PET) substrate. The obtained channel length is 100 µm, the channel width 6000 µm and 30000 µm for the load and the drive transistors, respectively. For the semiconducting layer, the commercially available polymer poly(9,9-dioctylfluorene-co-bithiophene) (F8T2) solved in xylene was printed by means of gravure printing on top of the source/drain structures. For the insulator a double layer approach was used [7, 13]. As low-k insulator a Butadien-Styren-Copolymer (BuS) and as high-k insulator Luxprint 8153E® were applied in a combination of gravure and flexo printing processes. On top of the insulator the gate was flexo printed from a silver filled ink.

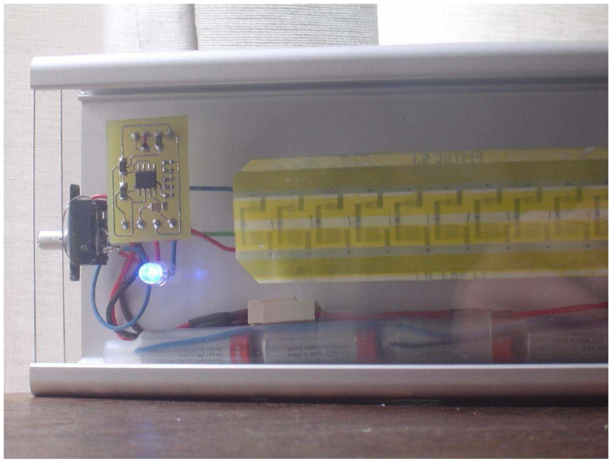

Fig. 2. The world's first all-printed integrated circuit, a seven-stage ring oscillator, used to drive a LED light.

(source: TU Chemnitz)

As can be seen in figure 1 the single inverter stages as well as the 7 interconnected inverter stages showed reasonable output characteristics. When the output of the last inverter stage was fed back to the input of the first one, one could observe an oscillation with a frequency in the order of 1Hz. As the oscillation is still relatively slow, a LED light was used as demonstrator. As can be seen in figure 2, the LED light was driven by the ring oscillator. The frequency of such devices is proportional to the mobility of the semiconductor and inversely proportional to the square of the channel length (i.e. the resolution of the source/drain structures). To reach the standard frequencies used in industry (e.g. 125 kHz and 13,56 MHz) a big progress in material properties and process development is necessary. For example, for a ring oscillator working at 13,56 MHz one would need a mobility in the order of 1 cm²/Vs and a resolution of 10 µm at a supply voltage of 10 V.

This work clarified a number of challenges regarding printing electronics. As can be seen in table 1 the requirements of conventional printing for visual output and for printed electronics are completely different. Since a large variety of materials with different properties is used, several mass printing methods have to be integrated in a single machine. Furthermore, the formulation of the printing inks has to be closely attuned to each other in order to avoid solving of underlying layers and to ensure good adhesion of the single layers on the underlying layer. Besides, the different lateral resolutions of the printing methods play an important role. Gravure and offset printing have the highest resolution, so that these are the methods of choice for the printing of high resolution source/drain structures. Resolutions of 10 µm and less are aspired. But in these dimensions, which are below the resolutions required in traditional printing, not only the process parameters and the ink formulation have to be accurately adjusted. Even the production of the printing form is a challenging task. For the printing of the semiconducting and insulating layer the requirements in terms of resolution are a little less restricted, so that also flexographic printing can be used. The choice of the printing method is therefore given by the properties of the available materials.

Fig. 3. Access-print ticket (left) and keyboard (right).

(source: printed systems, pictures: BurgEins)

Nevertheless, first commercial applications based on offset printing processes, similar to the one involved in the previously described experiment, are offered by the printed systems GmbH, a spin-off company of the Institute for Print and Media Technology at Chemnitz University of Technology. Their so called access-print playing cards, tickets and keyboards (see figure 3) rely on simplicity and inexpensive production instead of high performance. Conductive traces of PEDOT:PSS are printed on cardboards on a conventional offset press. After printing the conductive layer the product can be processed with standard methods like color printing, punching and gluing. The information is stored invisibly in the conductive traces. They can be read out either through electrical contacts or contactless capacitivity by small USB devices directly connected to the PC. First applications based on this technology are already on the market. These tickets and playing cards have already successfully demonstrated the use of mass printing methods for combining printing with electronic functionality.

In conclusion, today's organic electronics has reached a level where first applications, like RFID-tags and functional displays, have been demonstrated. On the other hand, printing of electronics is still at an early stage of development. In order to use mass printing methods for the fabrication of low-cost integrated circuits, a number of challenges in terms of resolution, layer quality and printing process parameters have to be solved.

However, there are already first simple applications, like access tickets or playing cards, which make use of the advantages of adding electronic functionality to printing products. These products are paving the way for printed electronics with higher complexity and functionality.

References

[1] W. Clemens et al., "From polymer transistors toward printed electronics", J. Mater. Res. 19(7), 1963 (2004).

[2] Philips, "Philips demonstrates world-first technical feasibility of 13.56-MHz RFID tags based on plastic electronics", Press Release, February 6, 2006.

[3] G.H. Gelinck et al., "Flexible active matrix displays and shift registers based on solution-processed organic transistors", Nature Materials 3, 106 (2004).

[4] C. R. Newman, et al.,"Introduction to Organic Thin Film Transistors and Design of n-Channel Organic Semiconductors", Chem. Mater. 16, 4436 (2004).

[5] T.B. Singh et al., "High Performance Ambipolar Pentacene Organic Field-Effect Transistors on Poly(vinyl alcohol) Organic Gate Dielectric", Adv.Mater. 2005, Vol.17, p 2315

[6] Y.Takahashi et al., "Organic Metal Electrodes for Controlled p- and n-Type Carrier Injections in Organic Field-Effect Transistors", Appl.Phys.Lett. 88, 073504 (2006)

[7] J. Veres et al., "Low-k Insulators as the Choice of Dielectrics in Organic Field-Effect Transistors", *Adv. Func. Mater.* 13, 199–204 (2003)

[8] H.Sirringhaus et al.," Enhanced Mobility of Poly(3-hexylthiophene) Transistors by Spin-Coating from High-Boiling-Point Solvents", Chem. Mater., 16, 4772-4776 (2004)

[9] S. Cichos et al., Proc. IEEE Polytronic 2002 Conference, 120 (2002)

[10] V. Subramanian et al., "Progress Toward Development of All-Printed RFID Tags: Materials, Processes, and Devices ",Proc. of the IEEE, Vol. 93, No. 7, 1330 (2005)

[11] PolyIC, "Pre-eminent innovation from Germany: Electronic products out of the printing machine draw nearer", Press release, December 2, 2005

[12] Philips, "Philips demonstrates world-first technical feasibility of 13.56-MHz RFID tags based on plastic electronics". Press Release, February 6, 2006

[13] D. Zielke et al., "Polymer-based organic field-effect transistor using offset printed source/drain structures", Appl. Phys. Lett. 87, 1, 2005, p. 87-89

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