Roll-To-Roll Printed Electronics

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Abstract

The fabrication of roll-to-roll printed electronics allows the mass production of microelectronic products in a cost-efficient way. Soluble semiconducting materials, an adjustment of existing printing processes and an adapted chip design pave the way for new products, such as flexible and transparent conductive films and printed "radio frequency identification" (RFID) tags.

A high resolution roll-to-roll production process was developed to achieve very small structure sizes down to 10µm on large areas with production speeds exceeding 30m/min. Two applications of printed electronics are presented: Transparent conductive films were realized by producing finely structured thin metal tracks on flexible substrates. Printed Manchester-encoded circuits and 13.56MHz RFID transponders were fabricated, which are based on the p-type semiconductor poly-(3-hexylthiophene).

Introduction

Organic or polymer semiconductors open new possibilities for the fabrication of microelectronic circuits. Many of them are soluble and thus can be processed from solution employing traditional printing processes. Considerable advantages are high production volumes and high production speeds, which give a cost advantage compared to traditional microelectronic circuits. Certainly printed electronics won't compete with the performance level of silicon circuits, due to much higher integration density and charge mobility attained in silicon technology. The prospect is to enable a sufficient performance and high volumes at low cost on places where no electronics can be found today. One promising application for printed electronics is radio frequency identification (RFID) [1,2], where silicon electronics suffers a lower cost limit and the requirements for performance is not too high for printed electronics. Another more simple application is to produce high resolution conductive tracks on flexible substrates to attain transparent conductive films [3] which can replace indium tin oxide (ITO), which is an expensive rigid material.

Roll-to-Roll Fabrication

RFID tags consist of different electronic components: Diodes and capacitors for rectification, transistors and vertical interconnects (vias) for logic circuits. These components contain different layers and the difficulty is to integrate all devices into one stack of conducting, semiconducting and insulating layers. We have developed a layer stack of 4 patterned layers out of which all devices can be realized (figure 1). The materials used are polyester with a thickness of 50µm as flexible substrate, metals like silver and copper for the bottom and the top electrode layers respectively, poly-3-hexylthiophene as p-type semiconductor and a blend of polymers as insulator.

In the selection of suitable processes different challenges have to be met for each layer. The bottom electrode has to be realized in high resolution, as it defines the minimum structure size of the transistors electrodes in the logic circuit. The more finely structured the electrodes are, the smaller the integrated circuit will be. We have developed a roll-to-roll production process where a resolution of down to 10µm is realized, e.g. channel length and finger width of a field effect transistors (FETs) in top gate setup are 10µm, as shown in figure 2. The insulating layer has to be applied in a pin hole free and homogeneous way in order to achieve uniform performance. The top electrode has to be printed in precise registration, to minimize circuit size. Furthermore, only non-toxic, non-explosive materials and solvents may be used in these processes.

At the actual stage of development several kilometers of printed electronics are produced each week at a production speed of at least 30m/min for each single machine in the production chain. Thus high volumes can be produced easily and no further upscaling will be necessary.

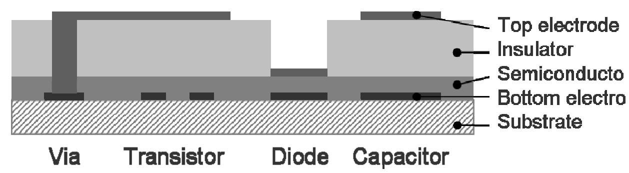

***Figure 1** Layer stack for integrated circuits, out of which all devices can be realized.*

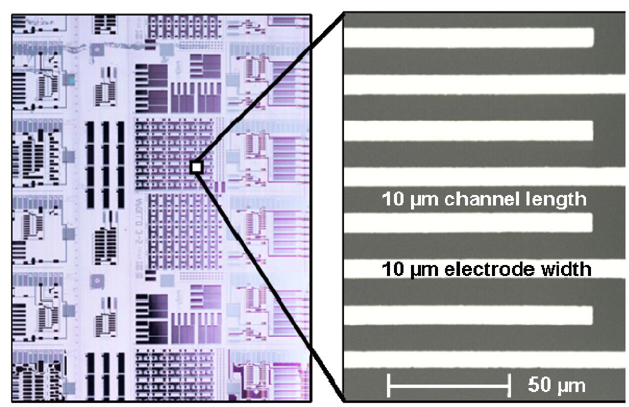

***Figure 2** High resolution production process allows minimum structure sizes down to 10µm. The magnification shows the bottom electrodes and the channel of a field effect transistor.*

Transparent Conductive Films

The high resolution roll-to-roll process permits a very simple application: A grid of conductive metal tracks appears transparent for the human eye beyond a certain resolution of about 50 to 100µm. This fact enables the fabrication of conductive transparent films, as the conductive metal tracks only occupy a fraction of the surface < 10%, the conductivity as well as the transmittance can be tuned by design. Figure 3 shows a comparison to alternative transparent conductive materials, e.g. PEDOT/PSS (polyethylenedioxythiophene / polystyrenesulfonate) or ITO (indium tin oxide). The transparent conductive film printed in high resolution shows higher transmittance and higher conductivity (that is lower sheet resistance) than the reference materials PEDOT/PSS and ITO. Furthermore compared to ITO they are flexible and the transmittance is higher over the whole visible wavelength range (figure 4). Therefore the transparent conductive film is suitable to replace ITO in many applications such as touch sensors in touch screen displays or electrode layers in organic photovoltaics.

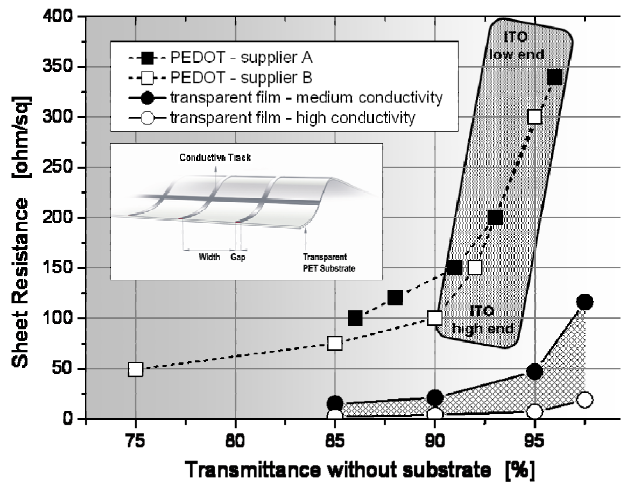

Figure 3 Sheet resistance versus transmittance (without substrate) plotted for PEDOT, ITO and the transparent conductive film. The inset shows a flexible sample of the latter.

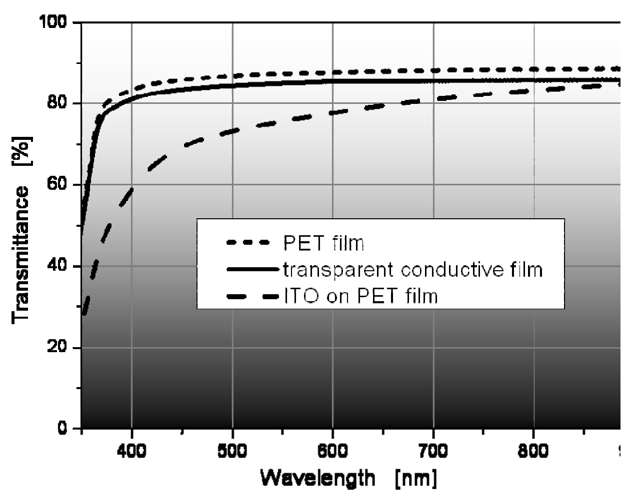

Figure 4 Transmittance across the visible wavelength range plotted for a PET film, the transparent conductive film and an ITO coated PET film.

Integrated Circuits

With the described roll-to-roll production process rolls of several kilometers in length containing thousands of electronic components and integrated circuits were produced. For inspection and optimization an appropriate testing machine capable of electrically measuring these rolls was set up.

Figure 5 shows the basic principle of RFID: a passive RFID tag is brought into the 13.56 MHz electromagnetic field of the reader where it absorbs energy. The energy absorbed is detected in the reader, and therefore by modulated energy absorption information is transmitted from the tag to the reader. Internally the RFID tag is set up as follows: an antenna picks up the electromagnetic field which is turned into a DC voltage by the rectifier, supplying the logic circuit. The stored data sequence is by load modulation transmitted to the reader.

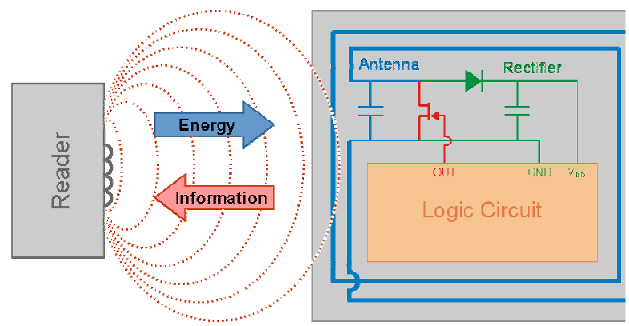

Figure 5 Basic principle of radio frequency identification: an RFID-tag receives energy and transmits its information in the electromagnetic field of the reader. The internal setup of the RFID tag is sketched as well.

An example of a possible logic circuit for RFID applications is a 4-bit Manchester-encoded chip. Figure 6 shows the block diagram which comprises the following modules: a ring oscillator with 15 stages as clock generator, a counter with 3 flip flops, a read-only memory with 4 bits, a protocol generator for Manchester-encoding and a modulator. Altogether the logic circuit is setup of roughly 200 individual devices. Figure 7 shows the measured signals, including the clock, the counter, the data sequence of the code generator and the load modulated rectifier signal. The programmed 4 bit data sequence “1001” is preceded by an idle time and a start bit, which allows a clear identification of the beginning and the end of the data sequence. The Manchester-encoding allows clock recovery.

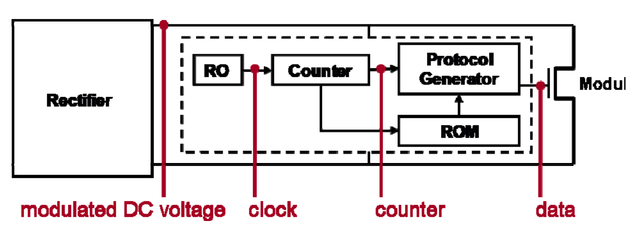

Figure 6 Block diagram of the printed 4-bit Manchester-encoded chip. The points of measurement are marked and the measured signals are plotted in figure 7.

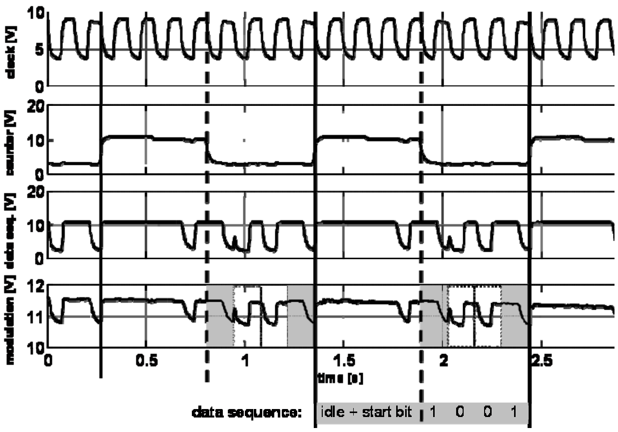

Figure 7 *Measured signals of the roll-to-roll printed 4-bit Manchester encoded chip.*

Conclusion

Two applications fabricated by a roll-to-roll printing process with production speeds of more than 30m/min have been demonstrated. Transparent conductive films based on finely structured thin metal tracks show suitable transmittance and conductivity to be considered an alternative to ITO films. A polymer RFID chip containing 4 bits of information transmitted by Manchester encoding was supplied by a 13.56 MHz rectifier and showed full operation.

References

[1] W. Fix, A. Ullmann, R. Blache, K. Schmidt, "Organic Transistors as a Basis for Printed Electronics" in "Physical and Chemical Aspects of Organic Electronics" (Wiley-VCH, Weinheim, 2009) pg. 3.

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[3] J. Wörle, H. Rost, "Invisible Helpers", Kunststoffe International 4 (2010), pg. 58.

Author Biography

Dietmar Zipperer studied physics at the University of York, UK and the University of Erlangen-Nuremberg, Germany, where he received a PhD for his work on polymer rectifiers in 2004.

He has worked for Siemens Corporate Technology, Erlangen, before he joined PolyIC at the formation of the company. He works as senior research scientist on the electrical characterization of printed electronics.