Preface

The Disruptive Potential of Low-Cost, Low-Temperature Technologies for Electronics

Electronics, and more specifically integrated circuits (IC), have dramatically changed our lives and the way we interact with the world. Following the so-called Moore's law [1], IC complexity is growing exponentially since 40 years, and this trend is predicted to continue at least for the coming 15 years [2]. The abundance of electronic functions at affordable cost has enabled a wealth of applications where the main IC strengths, namely computational speed and memory capacity, are well exploited: PCs, portable devices, game consoles, smart phones and alike. The commercial success of integrated electronics is based on a symbiotic development of technology and applications, where technical progress and economic growth nurture each other. This process requires lots of time and effort: first IC patents where filed in 1949 [3], but it is only in 1971 that the first commercially available microprocessor (Intel 4004), one of the most far-reaching application of ICs, gained the market; and PCs became popular only in the second half of the eighties.

The main strength of integrated electronics is in the low-cost-per-function enabled by an ever growing miniaturization: mono-crystalline silicon real estate is very expensive, but the number of transistors that can be integrated per area grows according to Moore's law, bringing down the cost to realize a given function.

Since the second half of the seventies, a completely different electronic paradigm, the so-called large-area electronics, has been developing. In this field the major aim is to decrease the cost per area (instead of the cost per function), enabling large surfaces covered with electronic devices. The main application of this kind of technology, typically based on amorphous or polycrystalline silicon transistors, is in active-matrix addressing of flat displays. The success of this technology has become evident in the last decade, when flat-panel LCD displays have swiftly replaced traditional cathode ray tubes in television sets.

Amorphous and polycrystalline silicon technology typically require high-temperature vacuum-based processing, with the consequence that glass substrates are used and that the technology throughput is limited. In the nineties a new technology approach has been proposed, based on materials that enable low-temperature processing and the use of very high throughput patterning technologies, borrowed from the graphic printing field: organic and printed electronics were born.

The word “organic electronics”, which I personally started using in 2000 [4] together with many colleagues, designates electronics manufactured using functional carbon-based materials, typically semiconductors, like pentacene, P3HT, PCBM, PTAA and many others. There are several reasons for this choice:

- Organic materials can form functional films when processed from solutions, paving the way to manufacturing processes with a reduced number of vacuum steps (which are typically expensive and cumbersome to scale to large areas), and thus enabling potentially very low-cost large-area electronics;
- Organic materials are processed at low temperature (typically below 200 °C), enabling the use of inexpensive and flexible plastic foils as substrates and paving the way to flexible electronics;
- Organic chemistry is intrinsically very rich, enabling the exploration of a limitless library of materials having very diverse electrical, optical, rheological and chemical properties;
- Together with the chemical variety, a large spectrum of physically different devices based on organic materials is possible and has been developed in the years, the most well-known being organic light emitting diodes (OLEDs) [5], organic thin-film transistors (OTFTs) [6, 7], organic photovoltaics (OPVs) [8], organic sensors [9], organic memories [10, 11], and organic MEMs [12][1].

Together with these strengths, functional organic materials and organic electronics present a number of drawbacks:

- Organic semiconductors have a relatively poor mobility, with peak values for single-crystal materials in the range of 10 cm^2/Vs [13], and typical values in solution-processed films of about 1 cm^2/Vs at the state of the art. Under this point of view, other materials suitable for low-temperature and large-area processing, like metal-oxide semiconductors and carbon nanotubes, may offer an advantage compared to organic semiconductors.
- Organic semiconductors (especially n-type) are sensitive to oxygen, moisture and other environmental aggressors, so that for long time organic electronic devices have had poor shelf and operational lifetime. Organic materials are also sensitive to bias stress, which tends to affect operational lifetime. Recent improvements in the materials, their formulation and encapsulation, however, show that instabilities should not be a show-stopper for commercialization (see for instance Sect. 2.3 in Chap. 2 and Sect. 4.4 in Chap. 4);

[1] In this section a few early and significant papers have been selected as references.

- Organic semiconductors are difficult to dope in situ with highly controlled dopant concentrations as a process equivalent of the ion implantation doping used in silicon has still not been developed for organic materials. This makes difficult to manage key parameters like transistor threshold voltages and injection barriers at the contacts.

Many more details on the state of the art and roadmaps of organic electronics are given in Chap. 1 and in the other chapters of this book.

The capability to deposit organic materials from solution makes possible to pattern functional materials using methods adapted from graphic printing, like inkjet, gravure, slot coating and many others. This leads to the concept of "printed electronics". The main strength of this approach is the high throughput that characterizes printing production processes, which means that printing has the potential to make possible very inexpensive large-area electronics, and thus to enable applications of electronics unthinkable till now. Moreover, printing is an additive process, thus only the functional materials that are needed are effectively used, contrary to the traditional lithography-based subtractive approach. This has the potential to decrease material usage and thus further bring down the costs. Detailed information on printing electronics is available especially in Chaps. 1, 2 and 6 of this book.

The strengths of printing are paired with the challenges that this technology faces: it is namely difficult and expensive to develop a new electronic technology using an approach that in a few minutes can generate rolls covered with hundreds of meters of electronics to be characterized and optimized. Uniformity, performance and yield are daunting tasks to be solved for future printed electronics applications.

The potential low cost, the compatibility with large flexible substrates and the wealth of devices that characterize organic and printed electronics will make possible applications that go far beyond the well-known displays made with conventional large-area silicon electronics. Organic and printed electronics can enable a true revolution in the applications of electronics: this is the view that brought me, together with a large number of colleagues, to write this book. The volume offers to the reader an extensive overview of the different devices enabled by organic electronics, and reviews a large variety of applications that are developing and can be foreseen for the future.

Chapter 1, written by Tampere University, the Organic Electronic Association (OA-E) and PolyIC, offers a complete *Roadmap for Organic and Printed Electronics* spanning till the end of this decade. It is an ideal starting point to understand the complex application scenarios and the likely developments in this rapidly growing technology domain.

In Chap. 2 by Konarka, Cyprus University of Technology and Friedrich-Alexander-University, are discussed *Organic Photovoltaics*, with great emphasis on the use of printing processes for their manufacturing. A wide overview of the printing processes for organic electronics is given, together with the state of the art of their application to solar cells. Photovoltaic cells do not need fine patterning of the structures in the plane of the device, and are thus an ideal candidate to exploit the high throughput of printing processes. This chapter is an excellent reading for the person willing to understand more about printing electronics. A roadmap for organic solar cells concludes this contribution.

In the third and fourth chapter light emitting diodes (OLED), the most advanced organic electronic devices available at the moment, are discussed. Chapter 3, written by Kyung Hee University and Samsung, gives a detailed overview of *OLED Displays*, a booming application that has reached the market since some years already, and is rapidly growing to become the standard emissive technology for flat displays. This section informs the reader about the different types of OLED pixels in commercial use and in development, and gives insight into the most relevant display and backplane issues.

Chapter 4, by Philips, gives a nice overview of *OLED for Lighting* applications. The section begins with an insightful description of the materials, physics, architecture and benchmarking of OLED lighting devices, to continue with an overview of fabrication methods, reliability and commercial applications.

Chapter 5 by University of Tokyo gives an interesting vision for future organic electronics: it will complement silicon ICs to create new applications enabling unprecedented ways of interaction between electronics and people. In this vision are included a variety of different organic devices (TFTs, sensors and actuators) providing a stimulating view on how different types of organic electronics can be integrated to enable revolutionary applications.

The sixth and seventh chapter deal with organic TFTs. Chapter 6 focuses on applications of *Printed Organic TFTs*. This section, written by PolyIC, describes the devices and technology needed to print transistors and circuits, the characteristics of printed TFTs, and what this revolutionary technology can mean in terms of applications (*RFIDs and Smart Objects*). Chapter 7 by IMEC, KUL, KHL, TNO and Polymer Vision focuses on the application of *Organic TFTs* to low-cost *RFIDs*. This section explains how organic RFIDs are developing towards becoming fully-compliant to existing standards for RFIDs based on silicon IC technology. Compatibility with standards would mean that the same infrastructure can be shared between silicon and organic RFIDs, enabling a seamless transition between the two technologies and an easy market uptake. This does not mean, however, that silicon and organic should serve the same markets: the characteristics of printed electronics lend themselves naturally to the dream of enabling item-level identification of retail items, which is still out of reach for silicon RFIDs, due to the high costs and cumbersome integration of silicon ICs with the items to be identified.

Chapter 8, contributed by University of California Berkeley, reviews the state of the art of *Chemical Sensors* based on organic electronic devices and demonstrates the specific competitive advantage that these sensors have, namely the ease of creating matrices of sensing elements with different sensitivity to diverse analytes, thus enabling the extraction of unique analyte signatures and greatly improving both specificity and versatility of use.

This book can be read at different levels of insight by beginners as well as by experts in the field, and is specifically conceived to address a wide range of people with technical and scientific background. I am deeply grateful to all contributors: I hope you will appreciate their effort and I wish you a pleasant and fruitful reading.

Eindhoven, The Netherlands, January 2012 Eugenio Cantatore

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