Chapter 2
Introduction to Organic Electronics

Organic electronics is forming a new basis for low-cost microelectronic technology on thin, lightweight and mechanically flexible substrates. The purpose of this chapter is to provide a general overview of the topic. The chapter describes the historical development of microelectronics starting from the evolution of vacuum tubes until the rise of organic devices, namely transistors, light-emitting diodes and photovoltaic cells. Emphasis is also made on recent leading advances in terms of materials, devices and applications.

2.1 History

Integrated circuits are often said to be the most important invention of the twentieth century. They have become ubiquitous in modern technology, finding their way into nearly all industries available including telecommunications, automotive, consumer electronics and many others [1]. An integrated circuit, also referred to as microchip, is a tiny electronic circuit in which all the components, such as resistors, capacitors and transistors, are housed on a single chip. Transistors, however, are the main building blocks of an electronic circuit; they are solid-state active devices, which act as switches or amplifiers [2]. Early transistors were discrete and large in size (few square centimeters), but the rapid pace of progress of integrated circuits has enabled packing of more than billion transistors onto a single chip (also with few square centimeters of area).

Before transistors and microchips, the electronic circuits were based on bulky devices and had to be painstakingly assembled piece by piece. The main family of such bulky devices was vacuum tubes (also called thermionic valves), which were used for rectification, amplification, switching or similar processing of electrical signals (Fig. 2.1). It was German scientist Heinrich Geissler who is credited with building the first vacuum tubes (also called Geissler tubes; they were almost completely evacuated) in 1855. He also noticed their strange glow of colored light when applying an electric field across the vacuum between two electrodes in 1857 [3].
It was described later that the colored light is caused by rays, called cathode rays, which are carrying negative electric charges and hitting the air molecules inside the tube to produce light. It was only 40 years later, in 1897, that the nature of the cathode rays was completely understood by the British physicist Sir Joseph John Thomson; he used the vacuum tubes to calculate the mass of the negative electric charges, which were suggested before to be particles and observed later to have properties of both particles and waves, and finally discovered the electron [4].

A series of subsequent configurations of the vacuum tube valves were essential in building early computers and marked the beginning of the electronics industry. German scientist Karl Ferdinand Braun invented in 1897 the cathode ray tube (CRT), which was then used to realize screens for television sets, oscilloscopes and radars [6]; British electrical engineer and physicist Sir John Ambrose Fleming invented in 1904 the diode valve, which was used for the rectification of electrical signals [7]; American engineer Lee de Forest invented in 1906 the triode vacuum tube (also called Audion tube or triode), which was used for the switching or amplification of electrical signals [8]. The vacuum tube valves, however, had many limitations; they were bulky, fragile, rather slow, difficult to miniaturize, consumed too much energy and produced too much heat [9]. For instance, the first general-purpose computer that was built in 1946, the ENIAC (Electronic Numerical Integrator And Computer), comprised more than 17 thousand vacuum tubes to perform operations and calculations, weighed about 30 Tons and filled an entire room. In addition, there was in average one tube of the ENIAC damaged every two days [10].

The idea of replacing these thermionic valves with more promising and reliable solid-state devices that are based on semiconducting materials can be traced back to the late-1920s and early-1930s. Three patents are considered as the foundation of the principles of solid-state devices those from American (formerly Austro-Hungarian) physicist Julius Edgar Lilienfeld (Author of the two patents [11] and [12] filed in 1926 and 1928, respectively) and German electrical engineer Oskar Heil (Author of the patent [13] filed in 1935). Both described in their patents different variations of a method, aperture or device to control the flow of an electric current between two
terminals of an electronically active material by means of a third potential applied to
an insulated third terminal. Lilienfeld suggested in [12] that the active layer could be
either pure metallic such as copper (Cu), compound such as cuprous oxide (Cu$_2$O),
or preferably, a mixture of both. Although Cu$_2$O is a semiconductor, there was
absolutely no definite indication in his claims of this class of solid materials or the
necessity of using it for the active layer. Heil, on the other hand, is believed to be the
first one who stated clearly in his patent that the active material should be made of
thin layer of semiconductor such as tellurium (Te) or cuprous oxide (Cu$_2$O) [14, 15].
He also described that the semiconducting layer changes its resistance depending on
the potential applied at the controlling metal terminal.

The presented inventions of Lilienfeld and Heil only embody concepts of solid-
state devices as possible substitutes for the thermionic valves, with no indication of
any reduction to practice. This class of solid-state devices was later named Field-
Effect Transistors (FETs), where the name transistor is a shortened version of the
original term transfer resistor, which conveys the operation principal of the device.
Subsequent to these key conceptual inventions, many electronic device physicists
and engineers pursued research on realizing semiconductor replacements for the
unreliable vacuum tubes. More than a decade later, in 1947, the first successful
semiconductor transistor was demonstrated [16–18]. This has marked the beginning
of a series of milestones, at which different device configurations and materials were
introduced. Four of the most important milestones are listed below:

- In 1947, American physicists Walter Brattain and John Bardeen demonstrated the
first transistor action in a germanium point-contact device [18]. The transistor
could amplify an input power up to 40 times [19], but had delicate mechanical
configuration and was difficult to manufacture in high volume with sufficient
reliability.
- In 1948, American physicist William Shockley invented the concept of Bipolar
Junction Transistors (BJTs) [20, 21]. At that time, Shockley was actually leading
a solid-state physics group at Bell Labs that included both Brattain and Bardeen.
All the three scientists were awarded the 1956 Nobel Prize in Physics for their
invention. For about three decades, the BJT was the main device of choice in
the design of discrete and integrated circuits. BJTs are nowadays mostly made
from silicon germanium (SiGe) and their use is often limited to very high-speed
applications such as radio-frequency circuits for wireless systems [1].
- In 1959, South-Korean physicist Dawon Kahng and Egyptian engineer Martin M.
Atalla demonstrated the first Metal-Oxide-Semiconductor Field-Effect Transistor
(MOSFET), which had been long anticipated by Lilienfeld and Heil [22–24]. The
device is mainly constructed by a stack of three layers: (i) silicon semiconductor as
a base material, (ii) thermally-grown native oxide as an insulator, and (iii) metallic
gate electrode as a controlling terminal. The MOSFET had largely superseded
the BJT, owing to many favorable properties of silicon, especially due to the con-
trollable and stable surface oxide. With the extraordinary progress and continued
miniaturization of the silicon-based technology, MOSFETs became the dominant
device used in integrated circuits and electronics industry until today (with the exception of large-area applications).

- In 1961, American physicist Paul Weimer developed the first thin-film transistor (TFT), which is a FET-like device similar to the ones proposed by Lilienfeld and Heil [25–27]. The TFTs are fabricated on an insulating substrate such as glass. In a typical process, TFT would comprise polycrystalline or amorphous semiconducting materials (only in some few cases crystalline semiconductors are used as well). For example, Weimer used a semiconducting film of polycrystalline cadmium sulfide (CdSe) in his first demonstration [25]. Unlike MOSFETs, TFTs are supreme for large-area applications that do not require significantly high speeds such as active-matrix liquid crystal displays (AM-LCDs). The most common semiconducting material used today for TFTs is hydrogenated amorphous silicon (a-Si:H), owing to its low fabrication cost and easy processability [28].

Ever since, the evolution and development of the semiconductor technology have been following two main approaches, namely silicon monolithic circuits and thin-film circuits. The advancement of both technologies has been aiming of shrinking device geometries, increasing production throughput and yield, improving circuit reliability and fault tolerance, minimizing mismatch effects and reducing manufacturing costs. The rapid pace of innovation for both technologies has been pursuing certain trends [29]. For example, one of the major trends that enabled the proliferation of silicon monolithic circuits until they became omnipresent today in our daily life is commonly known as Moore’s Law [30, 31]:

*Transistor density on integrated circuit doubles about every two years.*

—Gordon Moore (1965; updated 1975)

Increasing the density of transistors on chip implies more speed, complexity and functionality. Emerging applications, though, do require smarter integration by means of miniaturization (More Moore) as well as diversification (More than Moore). In recent years, mechanically flexible electronics as one of the approaches for diversification has caused a disruptive technology evolution and gained prominent market attractiveness for new user-friendly applications such as wearable devices, roll-screen displays and intelligent papers. This allows people as well as environment to interact with the complex information, which are typically processed by the high-performance miniaturized devices, in a more efficient and natural way.

A thin silicon chip is a possible solution, one that takes advantage of the crystalline silicon structure and leads to many high-speed flexible applications [32–35]. Nevertheless, an alternative solution is thin-film circuits that are based on a completely different class of materials such as organic semiconductors. Nowadays, organic materials are forming the basis of a new low-cost microelectronic technology that can be fabricated on large-area and flexible substrates such as polymer foils, papers or even fabrics. This is mainly owed to their low-temperature manufacturability, also to their (thermo) mechanical properties that makes them compatible with such kind of unconventional substrates [9]. One can envisage processing of this kind of
materials by printing methods, which enables low-cost, high-volume and high-throughput production [9]. The trend, however, for this large-area and flexible technology is to reduce the cost per unit area, instead of increasing the number of functions per unit area that is being followed by the crystalline silicon technology [29]. By combining both technologies in a so-called hybrid system-in-foil (SiF), one could actually take advantage of both worlds [33].

In fact, the first studies on the electrical activity of organic materials can be traced back to the early twentieth century [36]. Anthracene was the first organic compound in which photoconductivity was observed by Pochettino in 1906 [37] and Volmer in 1913 [38]. Later in the 1950s and 1960s, the potential use of organic materials as photoreceptors in imaging systems was recognized [36, 39]. During the same time, electroluminescence in organic compounds was observed by Bernanose et al. in 1955 by applying an alternating current (AC) in air to compounds such as brilliant acridine orange E [40] and by Pope et al. in 1963 by applying a direct current (DC) in vacuum to anthracene [41]. In spite of these handfull preliminary reports and principal demonstrations, the technological use of organic semiconductors was still very limited due to several drawbacks. First, the reproducibility and carrier mobility in organic semiconductors were very low. Second, the demonstrated devices were operating at extremely high voltages (e.g. 400 V) as a consequence of the crystal thickness (in the micrometer to millimeter range) and the difficulties to prepare stable, injection-efficient contacts to the compounds [42]. Third, the poor control of material purity and structure ordering were also obstacles. Finally, the materials used so far did achieve neither sufficient efficiency nor satisfying stability [42]. However, the research and interest in this field were flourished in 1977 by the successful synthesis of electrically conducting organic polymers through controlled halogen doping [43]. This discovery by Alan G. MacDiarmid, Alan J. Heeger, Hideki Shirakawa and co-workers was considered a major breakthrough, opened many new and exciting applications and honored with the 2000 Nobel Prize in Chemistry.

The first available organic materials were intractable, immobile, or even insoluble [44]. Nevertheless, the rapid advancement of the materials and processing has enabled the development of soluble organic compounds. Solubility is a key prominent feature, one that opened the possibility for cheap and high-volume production of printed electronics. Henceforth, the utilization of organic materials by various electronic components has given them, incontrovertibly, a place in the development of this theme [44]. Three components that can be considered as the foundation of organic electronics are organic photovoltaic cells (OPVCs), organic light-emitting diodes (OLEDs) and organic thin-film transistors (OTFTs):

First, the use of conjugated polymers, such as poly(sulphur nitride) and polyacetylene, for the realization of OPVCs were firstly investigated in the 1980s; their power conversion efficiencies, however, were well below 0.1 % [36]. A major breakthrough came in 1986 when American physical chemist Ching W. Tang discovered that a two-layer OPVC by bringing a donor and an acceptor in one cell could dramatically

---

1The carrier mobility is a measure of how fast an electric charge is transmitted through a material under an applied electric field and is mostly represented in units of cm²/Vs.
improve the efficiency to 1% [45]. Subsequent developments of OPVCs achieved in early-2013 efficiency as high as 12% according to recent announcements from the German company Heliatek [46].

Second, OLEDs in the form available today were firstly presented in 1987 by Ching W. Tang and Steven Van Slyke using a double layer structure of organic thin films (8-hydroxyquinoline aluminum Alq3 and aromatic diamine) [47]. Later, in 1990, the research on polymer electroluminescence culminated in the first successful demonstration of green-yellow polymer-based OLED using 100nm thick film of poly(p-phenylene vinylene) as an active layer [48]. The improved efficiencies combined with increased shelf and operating lifetimes, also superior material properties and manufacturing techniques, have pushed OLEDs already to the market place in applications like OLED-based lighting and displays. For example, the South-Korean company Samsung has just recently launched in August 2013 the first 55in. full high-definition\(^2\) (Full HD) OLED television with a curved panel (S9C series) [49].

Last, the debut of the field effect in organic semiconductors date back to 1970 [50–53], yet the potential use of the OTFT (at that time mostly referred to as metal-insulator-semiconductor field-effect transistor MISFET) as an electronic device was only identified in 1983 when Ebisawa et al. reported the first attempt to fabricate an OTFT that utilizes polyacetylene as an active semiconducting layer [54]. From this point forward, several studies were devoted to realize successful TFTs based on organic semiconductors such as polyacetylene [54, 55], polythiophenes [56, 57] and metallophthalocyanines [58, 59]. However, their carrier mobilities were very low in the range of \(10^{-4}\) to \(10^{-5}\) cm\(^2\)/Vs. It was not until nearly 7 years later, in 1990, that the carrier mobility in organic semiconductors approached and even reached that in amorphous silicon when Garnier et al. reported a carrier mobility as high as \(4.3 \times 10^{-1}\) cm\(^2\)/Vs for TFTs that used evaporated hexathiophene as an active material [60]. For comparison, the carrier mobilities in conventional a-Si:H TFTs are in the range of \(10^{-1}\) to 1 cm\(^2\)/Vs. The performance and stability of OTFTs have continuously improved since then. Hence, some OTFTs now compete with a-Si:H TFTs to enable revolutionary design possibilities in new large-area and mechanically-flexible applications. The most compelling application of OTFTs is backplanes for flexible active-matrix displays; accordingly, the German company Plastic Logic is currently manufacturing ultra-thin and lightweight plastic displays that are able to bend, twist and even roll-up like a piece of paper [61].

The field of organic electronics has been well-profiled and recognized by several international awards bestowed upon great scholars and scientists working on this subject. As mentioned above, the 2000 Novel Prize in Chemistry was awarded jointly to the Americans Alan G. MacDiarmid and Alan J. Heeger, and the Japanese Hideki Shirakawa for their discovery and development of conductive polymers [43].

\(^2\)The full high-definition (Full HD) is implying a resolution of \(1920 \times 1080\) (2.1 megapixel) in a 16:9 aspect ratio.
Furthermore, the 2010 Millennium Technology Prize\(^3\) was awarded to the British Sir Richard Friend (as one of the three laureates in that year) whose team discovered electroluminescent diodes based on polymers (PLEDs) and greatly participated in the development of OTFTs and OPVCs [48, 55]. In addition, the 2011 Deutscher Zukunftpreis\(^4\) (German Future Prize) was awarded to Karl Leo, Jan Blochwitz-Nimoth and Martin Pfeiffer for their major contribution in the advancement of organic functional materials and manufacturing techniques, especially for applications in lighting and photovoltaics [64–67]. Finally, it is worth mentioning that despite all these advances, the field of organic electronics is still in its infancy and there is still much room for improvement and much to be learned and investigated.

### 2.2 Materials

Organic electronics have been promising on account of their low-cost, low-temperature and fast manufacturability in addition to their compatibility with various kinds of substrates that are thin, large in area, transparent or mechanically flexible. In principle, organic electronics rely on electrically active materials that are based on conjugated organic compounds whose molecules contain carbon and hydrogen elements. A basic device, such as an organic transistor, is generally comprised of a stack of conducting, semiconducting and insulating thin-film layers. There are many attempts to realize all these layers solely from organic materials [68, 69]; however, they are mostly combined with special inorganic thin-films in order to optimize the device performance [70]. The structures and applications of the different organic-based devices are given in Sect. 2.3, where the different fabrication processes used to deposit and pattern the thin-film layers are discussed in Sect. 4.1. In this section, an overview of the different organic as well as inorganic materials is presented.

The materials are classified in this section as the following: (i) semiconductors, (ii) conductors, (iii) dielectrics, (iv) passivation, and (v) substrates. Each material in every class has its advantages and limitations, where often the process conditions as well as the interplay of the material with other layers have a large influence on the device performance [71]. Therefore, the selection of the materials has to be carefully done to meet application and technology parameters such as thermal, mechanical and optical properties. For example, transparency is very important for the realization of solar panels that are going to be mounted on building facades, but not for displays that are designed for e-book readers. A summary of the key application and technology parameters is listed below [71]:

---

\(^3\)The Millennium Technology Prize is the world’s largest technology award. It is awarded every 2 years by Technology Academy Finland, an independent foundation established by Finnish industry and the Finnish state in partnership [62].

\(^4\)The Deutscher Zukunftpreis (German Future Prize) is one of the most prestigious awards conferred for science and innovation within Germany. It is awarded annually by the Federal President of Germany [63].
• Electrical Performance—The performance (operation frequency, current driving capability) of the devices depends on the carrier mobility in the semiconductor, conductivity of the conductor and the dielectrical behavior of the dielectric material.

• Resolution and Registration—The reliability and performance of the devices depend on the lateral distance of the electrodes (pitch, or resolution) within the devices and the overlay accuracy (Registration) between different patterned layers. In addition, scalability is necessary to have a sustainable technology development.

• Environmental Stability—For the sustainability and proper lifetime of the devices, the sensitivity of the materials to oxygen and moisture has to be well considered. This depends also on the barrier properties of the protective sealing layers (substrate and encapsulation).

• Mechanics and Optics—The mechanical and optical properties include thin form factors, flexibility, bending radius, conformability, weight, transparency, color and appearance. Accordingly, the material, design and process have to be carefully chosen.

• Process Parameters—The process parameters include throughput, temperature and ambient conditions. For a reliable production, it is important to adjust the process parameters for the different employed materials.

• Cost and Yield—High volume production is only possible when the processes allow fabrication at an acceptable yield. This includes adjusted materials, circuit designs as well as in-line quality control for low-cost and low-requirement (e.g. disposable sensors) to high-cost and high-performance (e.g. flexible OLED display) products.

Semiconductors

Organic semiconductors are traditionally classified as small molecules\(^5\) or polymers\(^6\) [9]. Polymers often have excellent solubility, which makes them amenable to mass printing processes such as flexographic and gravure printing [70]. On the other hand, small molecules are usually deposited by vacuum sublimation; nevertheless, recent advancements enabled some of the semiconducting small-molecules to be processed in solution or dispersion [71], which makes them no longer restricted to evaporation/sublimation processes.

The carrier mobility is commonly used as a figure of merit to characterize the performance of materials, devices or fabrication methods. It is found that the carrier mobility in organic semiconductors varies greatly depending on the choice of material, its chemical purity and its microstructure, also on the process conditions and the interface to other layers in the device [9, 71]. For example, Fig. 2.2a illustrates the difference in the carrier mobility depending on the substrate temperature during deposition of the different semiconducting small-molecules. Furthermore, amorphous films

---

\(^5\)An organic small molecule is a compound containing carbon atoms that are bonded into stable individual molecular unit.

\(^6\)An organic polymer is a compound with a molecular structure formed from many identical organic small molecules bonded together.
Fig. 2.2 a Relationship between the carrier mobility in the transistor channel and the substrate temperature during the deposition of the organic semiconductor layer for five different small molecules: DNTT [74], pentacene [75], diethyl-sexithiophene [76], PTCDI–CH2C3F7 [77], F16CuPc [78], PTCDI–(CN)2–CH2C3F7 [79] and PTCDI–CH2C6H4CF3 [80]. b Development of the carrier mobility in organic transistors based on small molecules, polymers and single crystals. The data is categorized according to the deposition process, material class and type of injected carriers. The seven categories are the following (with reference to the publications from which the highest carrier mobilities are extracted): single crystals (p-channel [81]), vacuum-processed small molecules (p-channel [73] and n-channel [77]), solution-processed small molecules (p-channel [82] and n-channel [83, 84]) and solution-processed polymers (p-channel [72] and n-channel [85]). Adopted from [70] with permission from The Royal Society of Chemistry

of solution-processed semiconducting polymers usually have mobilities in the range of $10^{-6}$ to $10^{-3}$ cm$^2$/Vs [70]. However, the mobilities of certain semiconducting polymers can be increased to about 1 cm$^2$/Vs through molecular engineering and also by inducing semicrystalline order through better control of the film formation [72]. Small-molecule organic semiconductors, on the other hand, are often forming polycrystalline films when deposited by vacuum sublimation, which results in carrier mobilities as large as about 6 cm$^2$/Vs [73].

Figure 2.2b depicts the development of the best reported field-effect mobility of p- and n-channel OTFTs based on small-molecule and polymeric semiconductors since 1984. The carrier mobility in organic semiconductors, though still underperform that of the crystalline silicon, has improved dramatically until it approached and even surpassed that of the amorphous silicon (a-Si). Unlike inorganic semiconductors, organic semiconductors are not atomic solids but they are $\pi$-conjugated materials for which the charge transport mechanism is based on hopping between the individual conjugated molecules [44]. In this case, the mobility is mainly limited by trapping of charges in localized states [70, 86]. As for inorganic media, in a different manner, defaults such as traps, along with molecular and macromolecular structural irregularities, have a crucial impact on the charge transport [44].

It is very important to note that organic semiconductors are usually undoped (intrinsic semiconductors) and the notions of p- and n-channel OTFTs do not imply
the same meaning as for inorganic semiconductors. An n-channel OTFT is one in which electrons are more easily injected than holes. This has something to do with the matching of energy levels of the metal contacts and the semiconductor employed by the transistor as further clarified in the following chapter. The n-channel OTFTs are actually of special concern as they suffer from more than tenfold lower carrier mobility than their p-channel contenders (if in the same organic technology). In addition, they are highly sensitive to ambient conditions, especially to oxygen and moisture [87]. As a result, most organic-based circuits today make use of p-channel designs only [88, 89].

Several research efforts are currently devoted to realize stable n-channel OTFTs with relatively high carrier mobility as this enables the use of complementary circuit topologies, which offer higher-robustness, lower power consumption and larger noise-margin compared to unipolar circuits [90]. There are also other attempts to integrate the p-channel OTFTs with n-channel TFTs that are based on metal-oxide semiconductors (e.g. amorphous indium-gallium-zinc-oxide a-IGZO), as they can achieve electron mobilities larger than 10 cm²/Vs [91–94]. In general, the ongoing development of organic semiconductors is not limited only to the performance measures, but also extended to other essential issues such as lifetime in real-world environmental conditions, matching over large areas, reproducibility, production yield and operation voltage.

**Conductors**

The need for conductive traces in all electronic products is indispensable. As each conducting material has its own properties, the choice of the material strongly depends on the application. Conductive inks, which are typically consisting of micron-seized conducting flake particles, organic resins, solvents and rheology modifiers, are offering promising properties [71]. These compositions are compatible with a wide variety of substrates and are suitable for low-cost and high-speed manufacturing techniques such as screen and flexographic printing. For applications that demand highly conductive features, silver inks that can have electrical conductivity as large as $10^4$ S/cm is a preferable choice [71]. Examples of mechanically flexible applications that utilize printed silver inks are membrane touch switches, keyboards and on-chip antennas. Another favorable choice for less demanding applications is conductive carbon inks. In addition, some special compositions of carbon inks can also be used as resistors or positive temperature coefficient (PTC) heaters [71].

Moreover, some devices like OLEDs and OPVCs require not only mechanical flexibility and good conductivity, but also translucency or high transparency for their metal electrodes. In this case, inorganic conductors like indium tin oxide (ITO) or polymeric conductors like poly(3, 4-ethylenedioxythiophene):poly(styrene-sulfonate) (PEDOT:PSS) are possible solutions [70, 71]. Meanwhile, these materials are used already for applications such as touch screens and electrochromic displays. An alternative for ITO and PEDOT:PSS is a mesh of very thin (20–80 nm) and narrow (15 µm) metal layers (e.g. silver or copper). Such a pattern with a spacing of about 200 µm can achieve a transparency of about 65% over the entire wavelength range.
from 400 to 900 nm. For comparison, the transparency of an ITO film is ranging from about 60 to 85% for wavelengths from 400 to 900 nm, respectively [95].

For the OTFTs, material properties of the conducting layers, especially for the source and drain contacts, are very critical as they affect significantly the devices performance. The choice of the material in this case depends on the architecture employed by the OTFT, i.e., the order of which the device layers are deposited. The typical used materials are aluminum (Al) or chromium (Cr) for the gate electrode, and gold (Au) for the source and drain contacts [70]. For the design of an all-polymer OTFT, conductive polymers such as polyaniline (PANI) or PEDOT:PSS are also suitable for the gate, source and drain electrodes.

**Dielectrics**

Dielectrics are used in both active and passive devices such as OTFTs and capacitors, respectively. The majority of OTFTs to date have used inorganic dielectrics, mostly silicon oxide. In fact, the performance of the device depends strongly on the quality, physical properties and chemical nature of the insulator-semiconductor interface [9]. For instance, trapping states at the mentioned interface immobilize the carrier charges in the channel and correspondingly limit the performance [70, 87]. Significant improvements can be achieved as demonstrated in literature just by inserting few nanometers of organic single layer between the insulator and the semiconductor [96]. In order to take advantage of the complementary design features while not increasing the production cost, the challenge is to ensure that the dielectric material functions well with both p- and n-channel OTFTs.

**Passivation**

Passivation materials (encapsulation) are used to protect the devices against environmental influences such as scratches and degradation due to the presence of the water, oxygen or light [71]. In some applications, the use of encapsulation is highly necessary to ensure an adequate lifetime for the devices. As an example, OTFTs that are developed for medical applications can be encapsulated with poly(chloro-para-xylylene) (parylene) and gold layers to protect them against water [97].

**Substrates**

Finally, the substrate is the base material onto which the devices are manufactured. Key material parameters for choosing the substrate material are: optical transmittance, dimensional stability, surface smoothness, durability, barrier capability, temperature tolerance and mechanical properties (bending radius, deformation and hysteresis behavior) [71]. Nowadays, the majority of applications are using glass (also thin and flexible glass) or stainless steel substrates, also polymer substrates such as poly(ethylene terephthalate) (PET) or poly(ethylene 2,6-naphthalate) (PEN). In addition, paper (cellulose) or textile substrates are sometimes used.
2.3 Devices and Applications

Given the advances in chemicals and materials by international leading firms like DuPont in the USA and Merck in Germany, organic electronics promise real growth opportunities for developers in new innovative products, some of which are already translated into commercial reality. The flexible and large-area from factors as well as the potential low production costs of the organic technology are key benefits over their bulk, or rigid, silicon and other inorganic counterparts. The technology is versatile enough to be used in a wide range of applications as discussed herein. The organic materials can be combined to a number of active electronic components such as transistors, light-emitting diodes, photovoltaic cells, various types of sensors, memories or batteries, also passive devices such as conductive traces, antennas, resistors, capacitors or inductors [71].

2.3.1 Organic Light-Emitting Diodes

The most established and largest sector within the organic electronics industry, even by some margin, is OLEDs. Besides the display market, lighting applications have emerged recently as more than a niche market for OLEDs [98]. The basic device structure of an OLED is shown in Fig. 2.3a. The structure comprises two organic semiconducting layers, which are sandwiched by anode and cathode electrodes laying on a transparent substrate (e.g. glass). Depending on the transparency of the anode and cathode electrodes, the light is transmitted either from top, bottom or both directions of the device. This basic device structure is called heterostructure OLED, or sometimes referred to as bilayer structure, which resembles a pn-junction and is similar to the one used in the very first demonstration of an efficient electroluminescence (EL) OLED based on organic thin-films that was built in 1987 by Ching W. Tang and Steven Van Slyke of Eastman Kodak Co. [47]. In this structure, the two organic semiconductors function as a hole-transporting and light-emitting layers. To gain more insight about the exact role of the organic semiconducting layers, the operation is explained in the following.

The LEDs, regardless whether organic or inorganic, are principally operated by applying an external voltage across the pn-junction to accelerate charge carriers of opposite polarities, namely electrons and holes, from the cathode and anode contacts, respectively [99]. The carriers are driven towards the so called recombination region, which is located at the space charge region of the pn-junction and there the carriers form a neutral bound state, or exciton. It is called a recombination region because this is where the electrons recombine with the holes by falling into a lower energy level and realising energy in the form of a photon. The wavelength (color) of the emitted light depends on the bandgap energy of the materials forming the pn-junction. The recombination region, where the luminescent molecular excited states are generated, is typically very small in the single heterostructure LED and it is located at
the boundary between the two semiconductors. Therefore, to increase the probability of electron-hole recombination and improve the internal quantum efficiency\(^7\) of the device, an additional third semiconducting layer is exploited in a double heterostructure (O)LED. In this case, the three (organic) semiconductors function as electron-transporting, light-emitting and hole-transporting layers.

The organic semiconductors can be made of small-molecules or polymers. Depending on the materials used, the devices differ mainly in three criteria, namely fabrication technique and process controllability, operating voltage and efficiency\[^99\]. Small-molecule thin organic layers are mostly deposited by vacuum evaporation or sublimation, while polymer layers are usually processed in the liquid-state by spinning and solidification by heating. Control of the thickness of the organic thin-films in a spin-on technique is relatively harder than in vapor deposition. However, polymer-based OLEDs can usually operate at lower power than that of small-molecule-based OLEDs. This is owed to the high conductivity of organic polymers. The operation supply voltage of polymer-based OLEDs is in the range of 2–5 V, which is about 1–2 V less than that of small-molecule-based OLEDs. Furthermore, the efficiency of polymer-based OLEDs is typically higher than that of the small-molecule-based OLEDs. Nevertheless, focusing now on one single process or method would not be favorable, as the technologies are not mature enough to determine the optimal method. Display as well as lighting industries are currently focusing on different technical approaches for both solution- and vacuum-processable organic materials to develop cost-effective OLEDs.

For many years, the LCDs has been the norm for the display industries\[^98\]. However, the growing number of laptops, mobile phones, televisions and many other applications increase the demand for higher quality products. In contrast to LCDs, the superior virtues of OLED displays are the thinnest-ever form factor, deeper black levels when individual pixels switch off, and high contrast ratio. The main problem that was setting back the OLEDs for many years was the lifetime, yet it has continued to improve every year reaching now a sufficient level to compete with LCDs.

---

\(^7\)The internal quantum efficiency is the ratio of the number of emitted photons to the number of injected carriers.
Meanwhile, Asian companies such as Samsung and LG dominate the manufacturing of both LCD and OLED flat panel displays.

Another core competence of OLEDs is the lighting industry. In general, solid-state lightings (SSLs), including EL, LED and OLED lighting, are soon replacing the conventional lighting techniques such as incandescent combustion (candles and incandescent lamps) and gas discharge (fluorescent and induction lamps). SSLs have been promising on account their superior energy efficiency, absence of hazardous metals, flexible form factors, durability and their surface emission for design features. Exclusively, OLED lighting offer prospects for a vast number of unique features; this includes mechanical flexibility, large-area illumination, thinness of light-source, high efficacy and variable colours (including translucent colors) [71]. European companies like Philips and Osram are currently at the forefront in the development and production of OLED lighting. Figure 2.4a shows an example of an OLED lighting demonstration by Philips.

2.3.2 Organic Photovoltaic Cells

The other key component in organic electronics is photovoltaic cells. Today, the majority of commercialized solar cell modules are made of inorganic materials such as silicon [98]. However, the interest in organic photovoltaics is growing owing to the inherent capabilities offered by the materials; this includes the compatibility with low-cost reel-to-reel manufacturing, possibility to be fabricated on mechanically flexible substrates, less energy resources needed for production and reduced installation costs. The efficiency and durability of printed or vacuum-deposited OPVCs on flexible plastic or metal foils have been improving in recent years [98]. Rigid silicon will still dominate the fixed grid, large-area applications for many years to come; this is mainly because of the established and commercially proven production of silicon. However, more cost-effective photovoltaic technologies open the possibil-
ity to integrate renewable solar power generation in everyday structures and items. In addition, the mechanical flexibility enables to use OPVCs in clothing, bags and awnings to power wearable and portable electronic devices such as music players, mobile phones and tablets [98]. Moreover, the ability to fabricate OPVCs with customized transmission factors (transparency) offer prospects to integrate solar films as energy harvesting components in windows or building facades.

In principle, the progress and development of photovoltaic technology is divided into three generations [98]. The first generation is confined to the bulk, or rigid, silicon and other inorganic PVCs. This kind of PVCs typically comprise thin wafers of single-crystal or polycrystalline silicon, patterned with metallic electrodes and sandwiched between glass plates; these cells have today a maximum efficiency greater than 20%, where the theoretical maximum efficiency is about 30% [100]. The second generation is thin-film PVCs, which are made by depositing thin layers of silicon (Si), cadmium telluride (CdTe) or other materials on glass substrates using vacuum-coating techniques; this kind of PVCs are potentially cheaper than bulk silicon PVCs and have cell efficiencies in the range of 12% to 20%. Finally, the third generation is the OPVCs, which are mainly targeted to be incorporated into consumer electronic devices and they are expected to be even cheaper than thin-film PVCs. The record efficiency of OPVCs, however, is 12% as recently reported in January 2013 by Heliatek [46]. There are two types of PVCs that belong to the class of organic photovoltaics, namely dye-sensitized solar cells (DSSCs) and organic photovoltaic cells (OPVCs). In fact, the DSSCs mainly do not comprise organic materials with the exception of a thin film of organic molecular dye. Nevertheless, the DSSCs production and applications are similar to that of OPVCs. There is a mirror analogy between DSSCs, OPVCs and double-, single-heterostructure OLEDs, respectively.

First, the DSSC is composed of the following five layers (from top to bottom) [101]: (i) transparent top conductor with low series resistance, through which the light can be penetrated; (ii) porous semiconducting layer of titanium dioxide nanoparticles, which is used solely for charge transport; (iii) molecular dye that absorbs the light rays such as chlorophyll or porphyrin organic materials; (iv) electrolyte solution based on iodide/triiodide redox system, from which the electrons are recovered by the dye before decomposition; and (v) base conducting substrate that serves also as a counter electrode. The operation principle in this case is called artificial photosynthesis; the light enters the cell through the transparent top conductor, striking the dye at the surface of the semiconductor, where the charge separation takes place. Only photons with enough energy, larger than the bandgap of the dye material, are absorbed and are able to make the electrons in their excited state. Excited electrons are then injected directly into the conduction band of the semiconducting layer, through which they diffuse to the top-electrode (anode) to power the load. Before the dye molecules are decomposed, the dye recovers the lost electrons from the iodide in the electrolyte, oxidising it into triiodide. This reaction takes place before the injected electrons recombine to prevent short circuiting. Finally, the missing electrons needed to recover the trioxide then diffuses from the counter electrode (cathode), from which they are provided by the load.
Second, the structure and operation of OPVCs are similar to inorganic solar cells, where the incoming light creates electron-hole excitons, at the interface between the donor and acceptor. If a polymer donor is used, the electron-hole pair will have a binding energy of 0.1–1.4 eV, which is in fact larger than the few milli-electron-volts provided in the case of inorganic materials [102]. By applying an electric field, ideally all excitons are separated into electrons and holes that migrate to the corresponding electrodes, i.e., anode and cathode contacts. Referring to Fig. 2.3b, the simplest configuration that supports this kind of operation principle is the planar heterojunction (PHJ) solar cells; in this case, the donor and acceptor are sandwiched between a transparent anode (such as ITO) and a reflecting cathode (such as Al). However, the efficiency is limited here by the exciton diffusion length, which is about 3–10 nm in most organic semiconductors. Therefore, for a normal organic thin-film thickness of about 100 nm, most of the excited electrons recombine before reaching the electrode and the active region is only limited to a very thin region around the donor/acceptor interface, which is not enough to capture a reasonable amount of incoming light. For this reason, nano-structuring in bulk and ordered heterojunction (BHJ and OHJ) solar cells is investigated by researchers to alleviate this limitation.

A photograph of an OPV film produced at Heliatek is shown in Fig. 2.4b.

The most promising organic-based PVC design, however, appear to be the tandem cells, which stack several DSSCs or OPVCs [98]. The advantage of this stacked configuration is to increase the power efficiency by means of the following [102]: (i) reduction of the thermalization losses of high-energy photons by stacking different absorbers, (ii) absorption of the entire spectrum by optimizing each subcell to one part of the solar light spectrum, and (iii) compensation of the aforementioned problem of PHJ, i.e., the thin active region, by stacking a large number of subcells.

### 2.3.3 Organic Thin-Film Transistors

Organic thin-film transistors (OTFTs) offer prospects for a vast number of unique circuit applications in mechanically flexible, inexpensive, large-area and biomedical electronics. In principal, OTFTs are metal-insulator-semiconductor (MIS) field-effect transistors (FETs) in which the semiconductor is a conjugated organic material [70]. Figure 2.3c shows a basic structure of an OTFT; it is a three terminal device that consists of four thin-film layers deposited on an insulating substrate, namely gate electrode, gate dielectric, organic semiconductor and source/drain contacts. When a voltage is applied between the gate and the semiconductor, a thin sheet of mobile charges is created in the semiconductor in close vicinity of the semiconductor/dielectric interface [70], i.e., a channel is created between the source and drain contacts. This charge layer balances the charges of opposite polarity located on the gate electrode. By tuning the applied gate voltage, the charge density in the

---

8The diffusion length is the distance over which the excitons travel from the donor to the acceptor before undergoing recombination.
semiconductor channel is varied. Thus, the electric conductance of this channel is accordingly modulated.

There are four different possible (O)TFT planar configurations that are categorized according to the location of the gate and the source/drain contacts relative to the semiconductor layer, namely coplanar, inverted coplanar, staggered, inverted staggered structure [9, 14]. The transistor shown in Fig. 2.3c employs the inverted staggered (bottom-gate, top-contact) device structure. More details about the different device configuration are given in the following chapter. There are many different fields and applications in which the advantages of OTFTs can be exploited, but at this point, it is too early to designate one as a killer application. It is worthwhile to mention that there is a lot of movement and activity in this field through established and new start-up companies to develop novel and previously unexpected applications. Some of the major application areas of OTFTs are reviewed in the following.

One of the most important applications of OTFTs is radio-frequency identification (RFID) tags. They are frequency-coupled portable devices that are used to identify, track, sort and detect items or persons; they can be used in card authentication, ticketing, gaming and surveillance. Together with integrated sensors (e.g. temperature sensor [103]), low-cost RFID labels can be realized, which are able to monitor supply chains, ensuring for example that temperature-sensitive medicines, vaccines and food products are kept cool while being transported along extensive distribution network [98]. In an RFID, the communication takes place between a reader and a transponder (tag). The tag comprises a small chip and an antenna, where the antenna is solely used to couple RF energy from the reader into the tag; there are different coupling techniques, including backscatter, inductive and capacitive coupling. Organic RFID are expected to be deployed at the item-level as a smart replacement to barcodes. Using these tags for example in a supermarket would save much time by allowing customers to walk a cart that is full of goods past a scanner and the scanner would read all the items in the cart, create a list of the merchandise and finally calculates the total amount of charge in an instant; they could also be used to collect all the information about the products in the store and generate an inventory within a few seconds.

There are basically two types of RFID tags, namely passive and active tags. The passive tags do not employ an energy supply and they are merely activated by the reader, while the active tags comprise a battery (to enable larger reading distance) or sensors (to monitor data such as temperature). Although, the cost of silicon-based RFID has dropped to just few cents, the cost of assembly and packaging with the antenna and products is still high. As a result, the use of silicon-based RFID is limited to small-scale volumes. However, the potential ultra-low-cost production of printable OTFT-based RFID together with the antenna on thin plastic or paper substrates opens the possibility for individual item-level development. Companies like PolyIC in Germany and OrganicID in the USA are working on printed RFID based on OTFT, while others, such as Kovio in the USA, are developing printed RFID based on silicon inks. At this time, the performance and capabilities of printed organic-based RFID tags are lower than that of the silicon-based ones in many aspects like memory size, data rate and reading distances; however, the research is focusing now on the development of these aspects in addition to minimising production costs.
Introduction to Organic Electronics

Besides being used in RFID tags, printed memories are an attractive application for OTFTs, which gained also market attention. They can be used in various other devices that require information storage (e.g. games, sound, video and smart cards). Since most printed applications nowadays do not employ an integrated battery, non-volatile memories are generally used. Depending on the application, either ROM (Read Only Memory), WORM (Write Once Read Many memory) or NV-RAM (Non-Volatile Random Access Memory) are used. The company Thin Film Electronics ASA in Norway is an international front runner in the development and commercialization of printed memory devices based on polymeric materials [104].

Another key application of OTFTs is backplanes for mechanically flexible displays. Many flat panel displays are consisting of a matrix of pixels, formed at the intersection of rows and columns, where each pixel is an LED that is capable to emit light by being switched on or off [105]. Colored displays are realized by positioning matrices of red, green and blue pixels very close together. There are two ways to control the pixels and thus forming the desired image, i.e., either passive or active matrix driver methods are used. In a passive matrix, each row and each column of the display has its own driver. In this case, each pixel should maintain its state until it can be refreshed again. Passive drivers tend to be used only for simple and cheap modules because the realization of such kind of drivers gets more difficult when the current required to brighten a pixel increases and also when the area of the display increases. Consequently, active-matrix displays are used in such cases, where each pixel is efficiently addressed by incorporating a transistor (typically TFTs are comprised) in series that provide control over the current and hence the brightness of individual pixels. Therefore, smaller currents can flow in this case through the control wires and the wires can be finer as a result. This means that higher resolution is realizable. Furthermore, the transistor is also capable of holding the current setting, keeping the pixel at the required brightness until it receives another control signal.

This class of display drivers are currently being built by inorganic transistors (mostly using a-Si:H TFTs) on glass substrate, which forbid the capability of being mechanically flexible. Semiconductor materials such as conjugated organic compounds and metal oxides are being explored to enable the flexibility. Sony has demonstrated, in 2008, a bendable OLED display that is driven by OTFTs [106]; they have also proposed conceptual prototypes such as a laptop with flexible OLED screen and a wrist wearable music player at the 2009 CEATEC exhibition in Japan. Moreover, sony has announced in 2010 the first successful demonstration of an OLED panel that is capable of reproducing moving images while being rolled-up around a cylinder with a radius of only 4 mm [107]. These demonstrations are achieved by the integration of OLEDs and OTFTs on top of plastic films; these displays are thin, light-weighted, bendable, foldable and they can be rolled-up or dropped without being broken.

Besides backlit-LCD and LED flat panel displays that emit light, electronic-paper (e-paper), also referred to as e-reader, is another technology that imitates the appearance of ordinary ink on paper. The display elements used by e-papers feature a memory function that enable continuous display of the same image even if no current is driven. Furthermore, images can be changed using very low currents. An example
of such display elements is Electrophoretic cells. These features open the possibility to develop the backplane drivers for such kind of displays using OTFTs, which offer virtues in manufacturing flexible, thin, light-weighted and large-area e-papers at low production costs. The German company Plastic Logic is commercializing a range of high-quality plastic e-papers, which are shatterproof daylight readable displays and extremely flexible with proven lifetimes. Figure 2.4c shows one of their demonstrated displays that is driven by OTFTs. Just recently, in September 2013, a start-up company popSLATE in the USA had joined forces with Plastic Logic to create an always-on secondary screen display for Apple iPhones [108]. Owing to the unique and novel features of these displays, they can be easily embedded into accessory cases of smartphones or similar devices.

Likewise an OTFT-based active-matrix strategy can be used in large-area, low-end and conformable array of sensors and/or actuators. Electronic-skin (e-skin) that mimic the sensitivity of real skin is a good example [109, 110]. Considering the vast amount of pain receptors in a person’s skin and the large surface area of the human’s body, active-matrix driver holds a great advantage for such a sensor array. To gain more insight about the complexity, the human skin has more than two million receptors, which is equivalent to the number of pixels found in a typical high-definition television; moreover, an average adult’s skin exceeds two square meters of surface area, which is nearly as big as the largest flat-screen LCD television.

Researchers at the University of Tokyo demonstrated recently, in July 2013, the world’s lightest and thinnest flexible tactile sensor. This OTFT-driven prototype has a thickness of 2 µm, which is about one-fifth the thickness of plastic kitchen wrap, and comprises an array of 144 pixels over an area of 48 × 48 mm² [111]. In addition, this sensor could stand repeatable bending, be crumpled like a paper and accommodate stretching of up to 230%. It can also work at high temperatures and aqueous environments (e.g. in saline solutions), which enables the functionality of this sensor even inside the human’s body. This is considered as a major breakthrough to successfully mimic the sensitivity of a biological skin and opens up a wide range of new applications in fields ranging from healthcare and biomedicine to welfare [112]. For example, the same research group has used this ultrathin OTFT technology to realize a 64 channel surface electromyogram (EMG) measurement sheet for prosthetic hand control [113].

Other four examples of large-area sensors or actuators that could be driven by OTFTs are the following. First, smart textile carpets or mats, ones that are useful for safety or security purposes. For instance, they can be deployed in patient rooms in hospitals to indicate a dangerous fall, heart attack, stroke, or similar complications and accordingly warn the staff. Second, flexible sheet image sensors or photodetectors as demonstrated by ISORG (a start-up company in France) and Plastic Logic at the 2013 Printed Electronics USA. They have developed the first fully-organic image

---

9Electrophoretic cells are transparent microcapsules incorporating charged pigment particles. A matrix of these cells, sandwiched between two layers (top transparent electrode and bottom patterned line-electrodes), is forming an electrophoretic display. Depending on the individually applied electric field on each cell, or pixel, a visible image is displayed.
sensor with an area of $40 \times 40 \text{mm}^2$ and 8930 pixels, combining ISORG’s organic photodetectors with Plastic Logic’s OTFT backplanes [114]. Third, large-scale stress sensors that could be placed on a randomly shaped body such as a surface of a plane, allowing to detect micro-cracks soon enough during the flight. Finally, a sheet of braille actuators, which can be felt and read by blind persons. The same research group from the University of Tokyo has successfully developed in 2005 an integrated circuit card (ICC) that features a mechanically flexible braille display built in an OTFT technology [115].

Given the wide variety and novel features of organic semiconductors, OTFTs have been also explored for chemical and biological sensors [116]. Unlike the silicon-based technology (Chemically Sensing Gate Field-Effect Transistor ChemFET), OTFT-based sensors are promising on account of their upside-down device structure, which makes the semiconductor in direct contact with the analytes [117]. Examples of such parameters are the bulk conductivity, channel conductivity, threshold voltage and field-effect mobility. On the other hand, sensing occurs in the silicon-based technology at the gate or the gate/insulator interface and by indirect modulation of the drain current through capacitive coupling. In principal, organic conjugated compounds can perform weak chemical reactions with a variety of analytes, including both vapor- and water-based analytes as demonstrated in [118] and [119], respectively. Furthermore, it was shown in [118] that the response of different organic semiconducting materials to different analytes is distinctive. This facilitates the possibility to construct an electronic-nose (e-nose) with which an analyte (odor) can be uniquely identified from a coded reception of different organic semiconductors.

In addition, OTFT-based chemical and biological detectors are ideal for cheap, mass-produced, flexible sensors that can be used in a range of new disposable healthcare products. Using for example point-of-care (PoC) devices, people could diagnose or monitor illness quite easily in private, much like pregnancy tests and hygiene tests for life sciences and food handling applications. Companies and research facilities, such as Molecular Vision in the UK, Acreo in Sweden and VTT Technical Research Center in Finland, do have the vision to develop lab-on-a-chip technologies using organic semiconductors. This is to promote a more proactive approach to healthcare, with the onus on prevention of diseases and early self-diagnosis [98]. However, such a flexible system would require not only sensors but also circuits and other electronic components; this is commonly known as a system-in-foil (SiF) as discussed in the following.

### 2.3.4 Systems-in-Foil

Systems-in-Foil (SiF) are an emerging new class of flexible electronic products in which complete systems are integrated in thin polymeric foils [32]. This is achieved by combining sensors, displays, power sources (batteries or photovoltaics), circuits, discrete components and/or interconnect traces all in a thin polymeric foil (or in some cases on the foil) to give a flexible end product. Being very thin and easy to glue
to other substrates or even integrated into textiles, these systems can easily make arbitrary objects have smart interactive surfaces. In addition, they can also be fitted to existing equipment as retrofit sensors; for example, the power distribution of an equipment can be monitored using an attached temperature sensor foil [120].

As mentioned above, disposable biosensor systems are one example of SiF that could be used in different application areas such as point-of-care, food safety, environmental monitoring and agriculture [121]. Acreo is currently working on the realization of an all-printed biosensor system that includes battery, sensor, display and electronics on a single foil. Another example of SiF could be a contactless user interface, combining optical sensors, LEDs and flexible interconnects, as being developed by ISORG. Such a platform can allow hand proximity detection, gesture recognition or linear control. Furthermore, trading cards and board games could integrate RFID’s, displays or buttons in a form of SiF to add more functionalities and user engagement as well as authenticity when being susceptible to counterfeits [98].

Packaging is also a viable market for printed and organic electronics. The main role of packaging is to protect, advertise and provide information of its content, all at a cost commensurate with what is essentially a disposable item [98]. Currently, packages use low-cost holograms, watermarks, barcodes and safety labels as tools to indicate whether a product is real or fake. However, the idea of using low-end, mass-produced, printed RFID’s, sensors and optical feedback in a SiF could potentially provide new ways for simultaneously branding, promoting and protecting the products. This can only be feasible once the cost of printing such functional components becomes comparable to that of printing text and graphics on everyday packages, but this will take several years to achieve. Consequently, several technology start-ups and established suppliers of printing equipment are investing into reel-to-reel, high-throughput manufacturing of organic semiconductors. Until this technology comes to commercial reality, packaging companies, such as Karl Knauer in Germany, are developing and producing for example simple luminescent packaging [122].

Since lots of packaging and labels are made from paper-based materials (cellulose), there is also much research activity in paper-based electronics. For instance, a research group at the University of Cincinnati has been working on building circuits, displays and solar cells onto paper substrates [123]. Others, at Harvard University and the University of Washington, are trying to develop paper-based microfluidic devices as sensing elements. In addition, some of the paper manufacturers, such as Felix Schoeller in Germany, are active in this field; they are developing high-end coating techniques to produce high-quality, smooth paper substrates for printed electronics.

2.4 Summary

The electrical activity of organic materials has been explored since the twentieth century. However, these materials remained with no significant technological use for many years mainly due to their very low reproducibility and carrier mobility, poor
control of material purity and structural ordering, and process difficulties to prepare stable, injection-efficient contacts to the compounds. This was only until 1977 when the research and interest in this field were flourished by the successful synthesis of electrically conducting organic polymers through controlled halogen doping. Owing to the excellent solubility of many organic polymers, they are amenable to mass printing processes, which have been well established in the graphic art printing industry. This groundbreaking discovery by MacDiarmid, Heeger and Shirakawa was honored with the 2000 Nobel Prize in Chemistry. Henceforth, the utilization of organic materials by various electronic components, including transistors, light-emitting diodes and photovoltaic cells, has given them incontrovertibly a place in the development of this theme.

Organic electronics pose nowadays a strategic challenge to the market and they have shown lately a rapid progressive development towards higher level of integration and better performance. The carrier mobility in organic semiconductors, though still underperform that in the crystalline silicon and is likely to retain this position in the foreseeable future, has improved dramatically until it approached and even surpassed that in the amorphous silicon. In principle, the organic materials have to be carefully exploited since process conditions as well as the interplay with other layers (can be organic or inorganic thin films) have a large influence on the device performance.

The organic technology is versatile enough to be used in a wide range of new applications in fields ranging from healthcare to welfare, especially when flexibility, transparency, large area and/or low cost are paramount. Recent advances in organic materials have permitted a disruptive evolution in nearly all electronic products such as displays, lighting, power sources, sensors and integrated smart systems-in-foil. The following chapters are focusing on organic thin-film transistor (OTFT) fabrication, characterization, modeling and circuits design.

References

4. J.J. Thomson, Cathode rays. Philos. Mag. ser. 5 44(269), 293–316 (1897)
8. L. de Forest, Device for amplifying feeble electrical currents, U.S. Patent 841 387, 15 Jan 1907
References

11. J.E. Lilienfeld, Method and apparatus for controlling electric currents, U.S. Patent 1 745 175, 28 Jan 1930
12. J.E. Lilienfeld, Device for controlling electric current, U.S. Patent 1 900 018, 7 Mar 1933
13. O. Heil, Improvements in or relating to electrical amplifiers and other control arrangements and devices, U.K. Patent 439 457, 6 Dec 1935
33. J.N. Burghartz, You can’t be too thin or too flexible. IEEE Spectr. 50(3), 38–61 (2013)
40. A. Bernanose, Electroluminescence in organic compounds. Br. J. Appl. Phys. 6(S4), S54–S56 (1955)


92. G. Oike, T. Yajima, T. Nishimura, K. Nagashio, A. Toriumi, “High electron mobility (>16 cm²/Vsec) FETs with high on/off ratio (>10⁶) and highly conductive films (σ>10² S/cm) by chemical doping in very thin (~20 nm) TiO₂ films on thermally grown SiO₂,” in IEEE International Electron Devices Meeting Technical Digest, Dec. 2013, pp. 11.5.1-11.5.4
104. Thinfilm MemoryTM. http://www.thinfilm.no/products/memory/
120. L. Jamet, “Printed electronics opens up large flexible sensor design opportunities,” EETimes Europe, pp. 34–35, 2013
Short-Channel Organic Thin-Film Transistors
Fabrication, Characterization, Modeling and Circuit Demonstration
Zaki, T.
2015, XXIII, 220 p. 87 illus., 12 illus. in color., Hardcover
ISBN: 978-3-319-18895-9