

ZHENG CUI



PRINTED ELECTRONICS

MATERIALS, TECHNOLOGIES
AND APPLICATIONS



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MATERIALS, TECHNOLOGIES AND APPLICATIONS

Zheng Cui

*Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO),
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This edition first published 2016

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Library of Congress Cataloging-in-Publication data applied for

ISBN: 9781118920923

Set in 10/12pt Times by SPi Global, Pondicherry, India

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Preface

My involvement in printed electronics started in 2009 when I returned to China, after 20 years of working in the UK. My previous career was centered around the development and application of microfabrication and nanofabrication technologies. Going back to China gave me the opportunity to do something different. I joined the Suzhou Institute of Nano-Tech and Nano-Bionics, which is one of the research institutes within the Chinese Academy of Sciences, and set up the Printable Electronics Research Center (PERC) there with the help of start-up funds from the Institute and from the Administration of Suzhou Industrial Park where the Institute is located. Six years ago, printed electronics was quite a new field, particularly in China. The PERC that I set up was then the first research center dedicated to printed electronics R&D in China. Although I started on printed electronics from scratch, my previous years of experience on micro-nanofabrication helped me to understand printed electronics from the manufacturing perspective, which is different from those with a background in materials science. Printing is, after all, an additive fabrication similar to lithography-based micro-nanofabrication.

Over the last six years, PERC has built up a multidisciplinary research team and well-equipped laboratories. We decided to develop the technology from all directions, including synthesis and formulation of electronic inks, development of printing processes, printable thin-film transistors, photovoltaic, and organic light emission. We have even worked on encapsulation technology for organic electronic devices which are known to be susceptible to water and oxygen. The ultimate goal of PERC is to develop those technologies that could be useful and practical, eventually leading to some products that the market needs. With our efforts, we have achieved a great deal in the last six years. We developed a range of electronic inks from inorganic materials such as carbon nanotubes, metal oxides, copper and aluminum, and dielectrics, to organic photovoltaic and organic light-emitting materials. We developed a range of printing processes including inkjet printing, aerosol jet printing, gravure printing, gravure offset printing and screen printing. We succeeded in making thin-film transistors on flexible substrates using inorganic inks, making gravure and inkjet-printed organic solar cells, and making flexible organic light emitting diodes, as well as barrier films for encapsulation of organic devices. An innovative hybrid printing technique we developed has been implemented by industry to realize mass production of transparent conductive films for touch panels. We are very proud of what we have achieved in this new and exciting field.

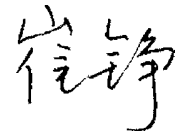
When we started working on printed electronics, we were very much aware that the field was not only new to us but also new to the majority of other scientists and engineers. This was particularly the case in China. We felt from very early on that more people should know about printed electronics and more researchers should get involved in the development, which is the only way to push the technology forward. So we began to plan a book. With the diligent work of my team, the Chinese book, *Printed Electronics: Materials, Technologies and Applications*, was published by the Chinese Higher Education Press in March 2012. This was the first book on printed electronics ever published in China. Three years have passed since this book was published. On the one hand, technology has moved on with new advances in the last three years. On the other hand, the authors of the first Chinese book have gained more experience by working directly in the field. It was time to update the book and we decided to write an English version to share the knowledge and information about printed electronics not only with readers in China but also with readers around the world. This English book is not simply a translation of the previously published Chinese book, but has newly updated information including some of our own work carried out at PERC in the past three years.

This book is written with members of my own research team, which is a multidisciplinary team with diverse backgrounds from physics to chemistry and to electronic engineering. Dr. Chunshan Zhou (author of Chapter 2 – the Chinese version of this chapter was written by Dr. Song Qiu who used to work at PERC) is an organic chemist at PERC working on organic semiconductor materials synthesis; Dr. Zheng Chen (author of Chapter 3) is leading the research at PERC on inorganic nanomaterials for electronic inks and printable inorganic thin-film transistors; Dr. Jian Lin (author of Chapter 4) is the expert on printing processes at PERC; Dr. Jianwen Zhao (author of Chapter 5) has been working on printed carbon nanotubes thin-film transistors since he was a postdoctoral researcher in Singapore six years ago. He has developed a range of techniques to purify and formulate single-walled semiconductor carbon nanotube inks and successfully printed high performance thin-film transistors; Dr. Changqi Ma (author of Chapter 6) is the leader of the organic photovoltaic group at PERC. With organic chemistry training during his Ph.D studies and a number of years of working in Germany, he has developed some new organic photovoltaic materials and is recently working on perovskite solar cells; Dr. Wenming Su (author of Chapters 7 and 8) is the expert on organic light-emitting diodes (OLED) and thin-film encapsulation at PERC, and is leading the engineering group at PERC. Since the authors themselves are directly practicing in their relevant topic area, they are well qualified to write on the topics. We put into the book not only the information and knowledge published by others, but also our own research experience and results. As the leader of PERC and the organizer of this book, I myself contributed Chapters 1 and 9, which reflect my understanding of printed electronics and my observation of the technological progress in the last six years with my deep involvement in the field. I also took charge of the English editing of all chapters.

There are already books published on organic electronics and flexible electronics. Printing as an alternative manufacturing technology gives organic electronics and flexible electronics extra dimensions and new application possibilities. We tried not to have too much overlap with organic electronics and flexible electronics. We organized the information we gathered specifically on printing and printed aspects of making electronics with or without organic materials and with or without flexible substrates. Printed electronics is still a growing field. The technology is still in its early stage of development. We hope that we have put together a comprehensive set of information and knowledge so that readers of the book will gain a general understanding of printed electronics, the materials and technologies that are involved in this

field and the potential applications. The contents have been organized and presented in a logical way so that people with a general knowledge of physics, chemistry and electronics will be able to comprehend. We hope that this book will serve as a guide for anyone who is interested in printed electronics and that useful information may be found in the book. Due to the limitations of our own experience and knowledge, there may inevitably be errors and inaccuracy of information in this book; we sincerely welcome comments and criticisms on the book from experts in the field.

Finally, I would like to give my sincere thanks to my team members at the Printable Electronics Research Center (PERC), Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO), Chinese Academy of Sciences (CAS). This book is truly the fruit of team effort. My acknowledgement also goes to the funding bodies that have provided major financial supports to my research team in the last five years under the National Key Basic Research Program of China (2015CB351900), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA01020304) and the National Natural Science Foundation of China (91123034).

A handwritten signature in black ink, consisting of stylized Chinese characters, likely '崔征' (Cui Zheng).

Zheng Cui

1

Introduction

Zheng Cui

1.1 What is Printed Electronics?

Printed electronics, as the name implies, is a type of electronics that are created by printing technology. To be more specific, it is an electronic science and technology based on conventional printing techniques as the means to manufacture electronics devices and systems. To most people, “printed electronics” is an unfamiliar phrase. Even experts in electronics may not have heard it. Many people may have it confused with conventional printing technology or mixed up with electronic printing. Conventional printing is for printing paper media, such as books, newspapers, and magazines. Even electronic printing is not printed electronics. Electronic printing is still conventional media printing but with more use of computers and electronic typesetting. A closer analogy to printed electronics would be electronics or integrated circuit (IC)-based electronics, rather than conventional printing. The aim of printed electronics is to make integrated electronic systems using printing technology instead of much more expensive and complex IC manufacturing technology.

Silicon-based IC technology has been in use for nearly 60 years. Modern silicon microelectronics and its manufacturing technology have evolved into an extremely complicated process. There are several hundreds of steps involved in producing a silicon IC chip, from the preparation of single crystal silicon substrates to making billions of transistors and getting these transistors interconnected, including repeated thin film deposition, lithography, etching, and packaging [1]. IC manufacturing has become so expensive that the latest deep UV photolithography system can cost tens of millions of dollars, whereas an extreme UV lithography system for making silicon chips at below 32 nm feature size has a price tag of more than \$120 million [2]. The IC industry has become so investment intensive that only a handful companies in the world can afford to play in the field. On the other hand, printing is a very simple process compared to the IC manufacturing process, as illustrated in Figure 1.1 In order to turn a functional material into a functional structure

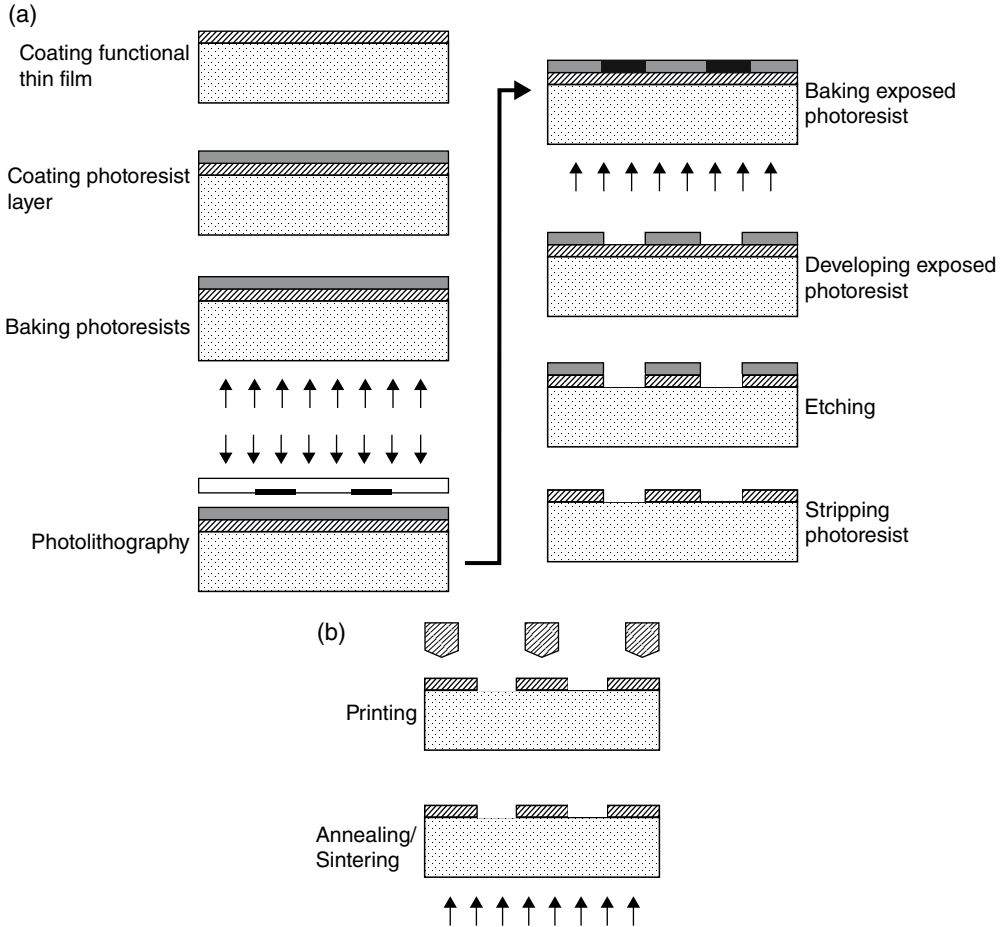


Figure 1.1 Comparison of IC manufacturing and printing processes. (a) Conventional IC manufacturing; and (b) printing process

or pattern on a silicon substrate, IC manufacturing has to go through thin film deposition, spin-coating photoresist layer, baking, photolithography, baking, developing, etching, and stripping of the photoresist masking layer. If printing is employed, the functional material can be directly printed as patterns onto the substrate. Only a subsequent annealing/sintering process is needed.

Printing is an additive manufacturing process, similar to the deposition process in micro- and nanofabrication [3] but combined with patterning. In printed electronics, the components of an electronic device or a system can be made by printing in additive fashion. For example, for a field-effect transistor, the source, drain, and gate electrodes, as well as semiconductor and insulating layers, can all be printed in ink forms and layer by layer onto a substrate. It is very much like color printing in a conventional printing press, where each color ink is printed sequentially and several color layers are overlaid to form the final color print. Because of its similarity to the printing process, the machine to print electronics is not much different from a conventional media printer. Figure 1.2 compares a conventional roll-to-roll paper media



Figure 1.2 Comparison of (a) conventional paper media printer; and (b) electronics printer. (Courtesy of iPEN Co. Ltd.)

printer and an electronics printer. They look almost the same. The only difference is the inks they use. The inks for printing electronics have conducting, semiconducting, or dielectric properties. They are electronic materials, not pigment, which is the key for printing to be used for printed electronics.

Printed electronics originated from organic electronics. In 1977, Alan Heeger, together with Alan G. MacDiarmid and Hideki Shirakawa, discovered that polymer could be conductive by doping certain molecules [4], which earned them the Nobel Prize in Chemistry in 2000. This discovery completely overthrew the conventional wisdom that organic polymer materials are always insulators. Following the discovery of conductive polymers, organic semiconductor materials were developed in 1983 [5] and organic field-effect transistors (OFETs) were first

Table 1.1 Charge mobility of organic and inorganic semiconductor materials

Semiconductor materials	Charge mobility ($\text{cm}^2\text{V}^{-1}\text{s}^{-1}$)
GaAs	10^4
Single-crystal silicon	10^3
Poly silicon	10
Amorphous silicon	0.1–1
Organic semiconductor	10^{-4} –1

made in 1986 [6]. In the same period, Dr. C.W. Tang at Kodak developed organic photovoltaic (OPV) materials [7] and later invented the organic light-emitting diode (OLED) [8], from which organic electronics as a field of scientific interest started.

The reason the scientific community got interested in organic electronics was not only due to scientific curiosity but more importantly that they foresaw the prospect of printing electronic devices from organic polymers that could be naturally made into ink forms. Once they could be printed, electronic devices could be made on a massive scale at low cost, very much like printing newspapers. So from the early stage of development, people made attempts to process organic electronic materials in solution forms to make transistors [9]. In 1994, a research group led by Francis Garnier first reported OFETs made on plastic substrates [10]. Although only electrodes were printed and the organic semiconductors were deposited by vacuum evaporation, the significance of the work was that it proved transistors could be made on plastic substrates, opening the era of plastic electronics. Fully printed transistors were reported in 1997 when Dr. Zhenan Bao, working at Bell Labs, printed all layers including conductor, semiconductor, and dielectrics onto polyester (PET) film by a screen printing technique [11]. More recently, Professor Sirringhaus at Cambridge University made fully printed organic transistors by the inject printing technique [12].

It is apparent that organic electronics had its eye on low cost printing electronics from the beginning of its development. However, for a very long period, printing did not become the mainstream fabrication means for making organic electronic devices. The main reason lies in the fact that the charge mobility, which is a key property of semiconductor material, for the solution form of organic semiconductors is always lower than those small molecular organic semiconductors that cannot be made into solution form and have to be deposited by vacuum evaporation. In other words, transistors made by printable organic materials are not as good as those made by vacuum evaporated organic materials.

Charge mobility is the speed of electronic charge (electrons for n-type semiconductor or holes for p-type semiconductor) movement in semiconductor materials. It determines how fast a transistor switches at an applied external electric field. Table 1.1 lists the charge mobility of commonly used inorganic semiconductor materials, in comparison with organic semiconductor. It shows that the charge mobility of organic semiconductor materials is far lower than inorganic semiconductors.

The research in organic electronics in its over 3 decades of development history has been mainly focused on how to improve the charge mobility, as it is obvious that only high mobility organic semiconductors have value in any practical applications. The last 25 years have indeed seen the steady improvement of charge mobility in organic semiconductors, as shown in

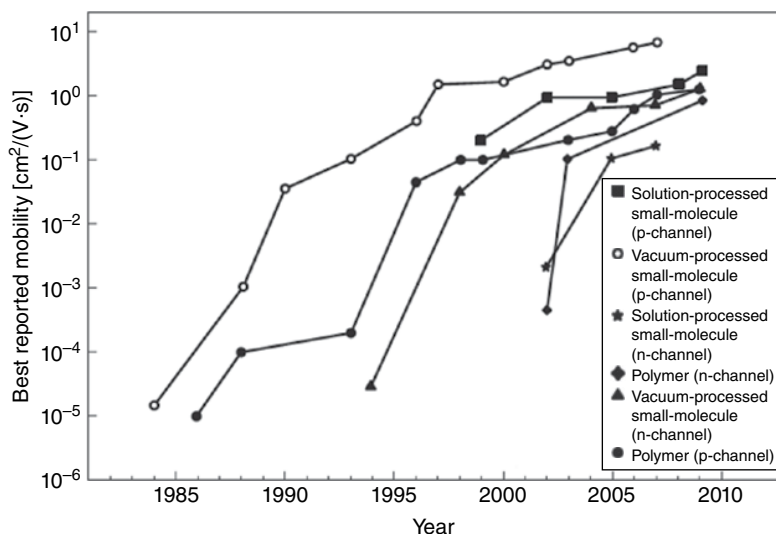


Figure 1.3 Evolution of charge mobility for organic semiconductor materials. (Adapted from [13] with permission from the Royal Society of Chemistry.)

Figure 1.3, which indicates the evolution of charge mobility from 1985 to 2010 for three different types of organic p-channel and n-channel semiconductor materials: vacuum-deposited small molecular organic materials, solution-processed small molecular organic materials, and solution-processed polymer materials [13].

The evolution curves reveal two things: first, there has been tremendous progress in improving the charge mobility of organic semiconductor materials. The mobility has increased 6 orders of magnitudes in the last 25 years. Second, the charge mobility of solution-processed polymeric organic semiconductor materials, though continuously improved, was always an order of magnitude lower than that of vacuum-deposited small molecular materials throughout the 25 years of development. Though the gap became smaller in the last few years due to the efforts in solution forms of organic semiconductors, small molecular organic semiconductor materials are still far better in terms of charge mobility [14]. As the ability to process organic semiconductor in solution form is the prerequisite of printing fabrication, low performance has prevented printing from becoming the preferred means of making organic electronic devices, although to be able to print electronic devices was originally the goal of organic electronics development.

Comparing the charge mobility of organic electronic materials in Figure 1.3 with that of inorganic semiconductor materials in Table 1.1, one can see that the mobility of organic semiconductors only barely catches up with that of amorphous silicon and is 3 orders of magnitude lower than single crystal silicon, which is the most common semiconductor material in IC microelectronics. According to the roadmap of organic semiconductors published in 2013 by the Organic Electronics Association (OE-A), as shown in Figure 1.4, the charge mobility of organic semiconductor materials may increase an order of magnitude higher than the current level in the next 10 years. Beyond that, organic semiconductors may reach their limits and inorganic or nanomaterials may come into play [15]. Besides, it would be difficult to change

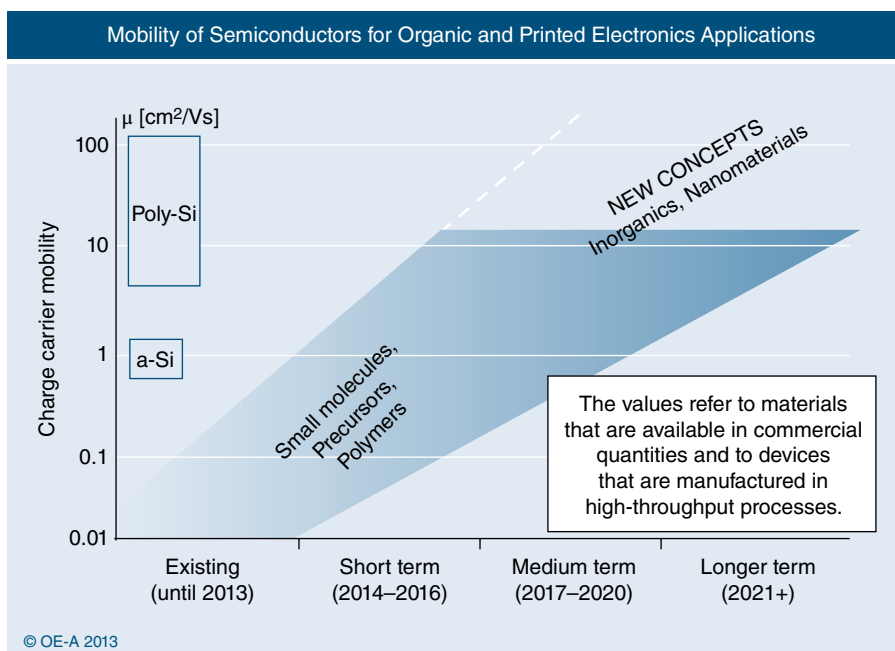


Figure 1.4 OE-A roadmap for the charge carrier mobility of organic semiconductors. (Reprinted from [15] with permission of OE-A.)

the fact that vacuum deposited small molecular organic semiconductors are always better than the printed solution form of organic semiconductors. The most obvious example is OLEDs. The best-performing OLED devices, no matter for lighting or for display, are still manufactured by vacuum deposition instead of printing. Printing has not succeeded in becoming the mainstream manufacturing technology for organic electronic devices, though some promising developments have been reported recently in printed OLEDs.

Printed electronics gained attention only in the last 8 years or so, largely due to the development and maturity of inorganic nanomaterials. Nanoscale inorganic materials (nanoparticles, nanowires, nanotubes, etc.) can be made into ink forms that can then be printed into patterns. The properties of those nanomaterials give the printed patterns and structures the conducting, semiconducting, dielectric, and optoelectronic properties that form a variety of electronic, optoelectronic, or photovoltaic devices, demonstrating that printing can be truly a low cost electronic manufacturing technology. Printed electronics began to establish itself as an independent scientific discipline and technology field. Scientific publications related to printed electronics started to increase, as indicated by the number of papers listed in the Web of Science database in the 10-year period up to 2013 (Fig. 1.5). International conferences and trade fairs in the theme of printed electronics began to appear. The first International Exhibition and Conference for the Printed Electronics Industry (LOPE-C) was held in 2009 in Germany. In the same year, South Korea hosted the first International Conference on Flexible and Printed Electronics (ICFPE). These conferences have become the focus of the printed electronics research community and industry. The 2015 LOPE-C drew more than 2,300 visitors from 42 countries.

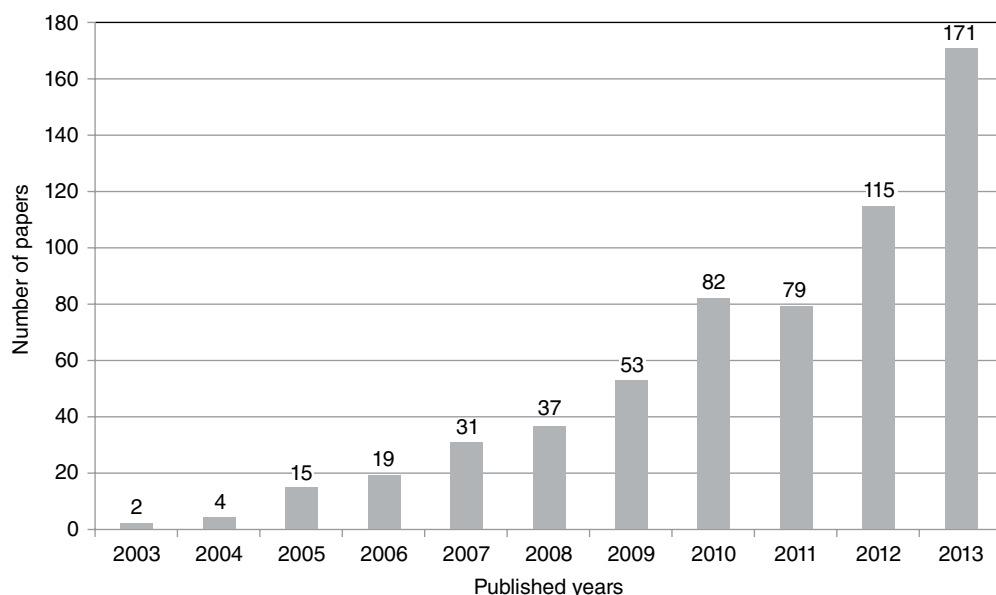


Figure 1.5 Published papers with “printed electronics” as key words. (Statistics from Web of Science database.)

An article published in *Plastic Electronics* magazine in 2011, titled “Nanomaterials Are Becoming Synonymous with Printed Electronics” [16], reflected the view that inorganic nanomaterials have revived printed electronics.

The earliest adopted inorganic nanomaterial in printed electronics is nanosilver. It is known that silver is the best conductive material, far better than organic conductive polymers. Silver nanoparticles can be made into paste or ink and printed. After sintering, the printed silver patterns become solid silver, which serves as a conductive track in a variety of electronic circuits. In fact, silver paste has long been used in silicon solar cell manufacturing. Figure 1.6 shows a silicon solar cell where those bright tracks are silver electrodes made by screen printing of silver paste. Although printed, the silver paste used in silicon solar cell manufacturing is not made of silver nanoparticles but microsize particles. The difference between nanosilver and microsilver is the sintering temperature. For microsilver, the sintering temperature needs to be more than 400°C in order to turn the silver paste into solid silver. Such high temperature is, however, not applicable to plastic substrates. Silver paste or ink made from nanosilver with particle size below 100 nm, on the other hand, can be sintered at below 150°C, which is the temperature most plastic film substrates can bear.

Nanosilver inks can be printed by a variety of printing methods such as inkjet printer, screen printer, gravure printer, or flexographic printer. Figure 1.7 shows a flexible circuit made by printing nanosilver ink on PET substrate. The emergence of nanosilver inks opens the route to printing conductive patterns onto plastic or even paper substrates with performance near or better than conventional copper-based conductive circuits. The electronics industry has already been testing the feasibility of printing electronic circuit boards, antennas of radio frequency identification (RFID) tags. Recently, inks made of silver nanoparticles or silver nanowires have

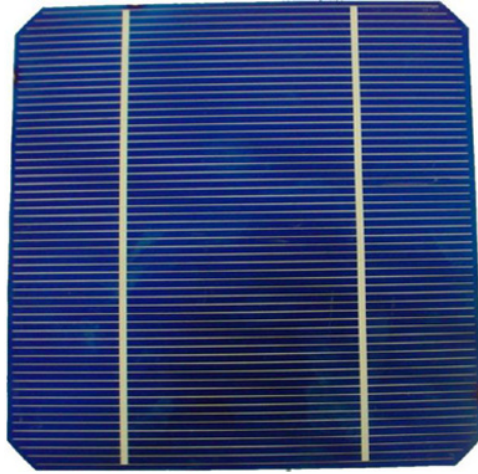


Figure 1.6 Picture of silicon solar cell where the front conductive electrodes are made by screen printing silver paste



Figure 1.7 Flexible circuits on transparent plastic film made by inkjet printing of nanosilver ink

been applied to make transparent conductive films that can replace indium tin oxide (ITO) to be used in touch panels for mobile phones and tablet computers. These are the products conventionally made by photolithography and etching processes that are wasting large quantities of materials and polluting the environment.

In addition to conductive nanomaterials, inorganic semiconducting nanomaterials also demonstrated their superior performance in printed electronics. Although organic semiconductor

materials have advanced considerably in the last 5 years with charge mobility approaching $10 \text{ cm}^2\text{v}^{-1}\text{s}^{-1}$ [17], single-walled semiconducting carbon nanotubes can have charge mobility exceeding $10^4 \text{ cm}^2\text{v}^{-1}\text{s}^{-1}$. Such high charge mobility has been proved in field-effect transistors made of single carbon nanotube. They have also been made into ink forms and printed to make field-effect transistors. Though not as high as that of single carbon nanotube, the charge mobility of printed transistors using carbon nanotube ink can easily get to more than $30 \text{ cm}^2\text{v}^{-1}\text{s}^{-1}$ [18]. Inks made of nanosilicon have been successfully printed to make fully functional 128 bits RFID with effective charge mobility exceeding $100 \text{ cm}^2\text{v}^{-1}\text{s}^{-1}$ [19]. Another family of inorganic semiconductor inks based on doped InO or ZnO has also found applications in printed transistors and demonstrated high charge mobility [20, 21].

Besides charge mobility, another critical issue concerning organic semiconductor materials is the environmental stability. Most organic semiconductors are very sensitive to oxygen and water vapor, which can kill their charge transportation ability. For OPV materials, the water vapor transmission rate (WVTR) should not exceed $10^{-4} \text{ g/day/m}^2$. For OLED, the WVTR should be less than $10^{-6} \text{ g/day/m}^2$, which is equivalent to less than a drop of water on a $50 \times 100 \text{ m}$ football pitch for a month. With such a strict requirement, any devices employing the organic materials have to be made in an oxygen-free and moisture-free environment and tightly encapsulated. For devices made on glass substrates, this requirement is relatively easy to realize because the sealing only needs to be implemented at the edges between two glass panels. For devices made on flexible plastic substrates, it is difficult to fulfill the requirement, and barrier layers have to be applied to the entire surface of plastic substrates. Effective barrier materials and coating techniques should meet the $10^{-6} \text{ g/day/m}^2$ WVTR requirement. Therefore, one of the intensively studied areas in organic electronics is to develop environmentally stable organic electronic materials as well as effective barrier-coating techniques. In contrast to organic electronic materials, inorganic materials do not have the environmental stability issue. Printing of inorganic nanomaterial inks can be done in an ambient environment and printed devices do not need special care for encapsulation. Therefore, printed electronics is relatively easy to implement with inorganic nanomaterials. It is fair to say that the use of inorganic nanomaterials has brought printed electronics closer to market.

Organic electronic materials have their own merits when applied to printed electronics, despite the above-mentioned problems. Though inorganic nanomaterials have their distinctive advantages over organic materials, they have their own issues when applied to printed electronics. The advantages and disadvantages of both categories of materials are summarized in Table 1.2 and 1.3. Detailed explanation for the tables will be given in Chapters 2 and 3 of this book. One can see from the tables that these materials are far from perfect and mature for printed electronics. A lot of research and development needs to be done in printable electronic materials, as well as in printing technologies and in various applications.

Table 1.2 Pros and cons of organic materials for printed electronics

Advantages	Disadvantages
Designability of organic molecules	Low charge mobility
Low annealing temperature	Poor environment stability
Flexibility	Poor printability of small molecular materials
Better printability of polymer materials	Batch to batch inconsistency

Table 1.3 Pros and cons of inorganic nanomaterials for printed electronics

Advantages	Disadvantages
Inherently high charge mobility	Difficulty in ink formulation (separation and dispersion issues)
Environmental stability	Impurity due to surfactants
Mature manufacturing technology	High post-processing temperature
Abundantly available	“Coffee-ring” effect
Batch to batch consistency	Inferior property compared to their bulk form

Table 1.4 New classes of electronics and their key features

Terms	Active materials	Substrate materials	Fabrication methods
Organic electronics	Organic polymers or small molecules	Any rigid or flexible materials	Thermal evaporation, coating, or printing
Plastic electronics	Organic polymers	Plastics	Coating or printing
Flexible electronics	Organic or inorganic materials	Flexible metals, plastics, or glass	Coating, printing, or surface mounting
Paper electronics	Organic or inorganic inks or pastes	Paper	Coating or printing
Transparent electronics	Transparent organic or inorganic materials	Transparent rigid or flexible materials	Printing or photolithography
Textile electronics	Organic or inorganic inks or pastes	Textile or fabric materials	Printing or weaving
Wearable electronics	Organic or inorganic inks or pastes	Flexible and stretchable materials	Coating, printing, or surface mounting
Printed electronics	Organic or inorganic inks or pastes	Any rigid or flexible materials	Coating or printing

When defining printed electronics, one should be aware of a few other newly emerged electronics; for example, organic electronics, plastic electronics, flexible electronics, paper electronics, transparent electronics, textile electronics, and wearable electronics. They all represent a new class of electronic technologies that are different from the silicon-based microelectronics. Table 1.4 gives a rough guide on what the key features are for each category of the new electronics.

Organic electronics refers to those electronic devices whose active materials, that is, the materials enabling electronic charge transport in a device, are organic in nature, whether they are organic polymers or organic small molecules. Organic electronic devices are not necessarily flexible. They can be made on glass or silicon substrates as well. Plastic electronics, though almost the same as organic electronics, refers exclusively to organic electronics on plastic substrates. The key feature of flexible electronics is the flexibility. To be flexible does not have to be on plastics. Thin sheet of metals or glass can be flexible. The reason that metals or glass are used as the substrates is their ability to withstand high annealing or sintering temperature. As one will learn from the rest of this book, some electronic inks, especially inks made of inorganic materials, require high temperature to sinter. To make electronics flexible, one can also

simply mount silicon chips onto plastic substrates. Though not flexible microscopically, the whole electronic system can be flexible macroscopically [22]. Paper electronics is quite straightforward to understand. No matter what materials are used to make the devices, they have to be on paper substrate. Transparent electronics requires not only transparent substrates but all the electronic materials have to be transparent. Textile electronics is electronic devices or systems on cloth, either weaved into a cloth with electronically functionalized fabrics or printed/mounted onto the surface of cloth. Wearable electronics generally refers to electronic devices that are small and lightweight and can be wearable, for example, the Google Glass and the Apple Watch. Compared to all the aforementioned electronics, printed electronics differs from all the others only in the way the electronic devices are fabricated. Printed electronics encompasses the other electronics, because both organic and inorganic electronic materials can be printed and electronic devices can be printed either on rigid substrates or flexible substrates, whether on papers, plastics, textiles, or glass.

1.2 The Importance of Developing Printed Electronics

Why are organic electronics, flexible electronics, or printed electronics being developed? It is because these electronics are different from the familiar silicon microelectronics with two distinctive features: one is the additive fabrication process in which electronic materials are added layer by layer to make a device; the other is that the functionality of a device is independent of substrate materials. The first feature enables printing as a means of device fabrication, which is less waste of materials and less energy consumption compared to thermal evaporation or sputtering deposition. The second feature enables many cheap materials other than silicon to be used as substrates. The combination of these two features makes it possible to manufacture large-area, flexible, green manufacturing, and low cost electronic products. For example, the largest size of silicon wafer by far in IC manufacturing is 12 inch (300 mm), whereas printing can work with sheet size of easily over meters; using plastic films as substrates, whether information displays or solar cells or lighting panels, can be flexible, lightweight, or even transparent; printing manufacturing, with its high throughput capability and low cost of equipment and ink materials, can significantly lower the cost of final products. In addition, the additive manufacturing process is green, meaning no subtractive etching involved, no high temperature processes needed, hence low in energy consumption, material waste, and environment pollution.

Can printed electronics replace silicon microelectronics? The answer is no. There is no doubt that printing is a simpler and faster manufacturing technique than lithographic patterning for silicon microelectronics, as illustrated in Figure 1.1. However, printing does not have the accuracy and resolution capability of modern lithography techniques widely used in the IC industry. Modern IC chips have minimum circuit feature size less than 20 nm, whereas modern printing machines can only print features of a few micrometers at best, which is a thousand times larger. The best organic or inorganic semiconductor materials that are printable are still 2 orders of magnitude poorer than the basic semiconductor materials used in IC chips. Therefore, the performance of printed electronic devices is nowhere near the performance of silicon microelectronics. Performance versus cost when comparing printed electronics with silicon microelectronics could be shown as in Figure 1.8. Though the performance of printed electronics is poorer, it is cheaper. In addition, printed electronics can offer large size and flexibility that silicon microelectronics cannot. They are not to replace each other but complementary to each other.

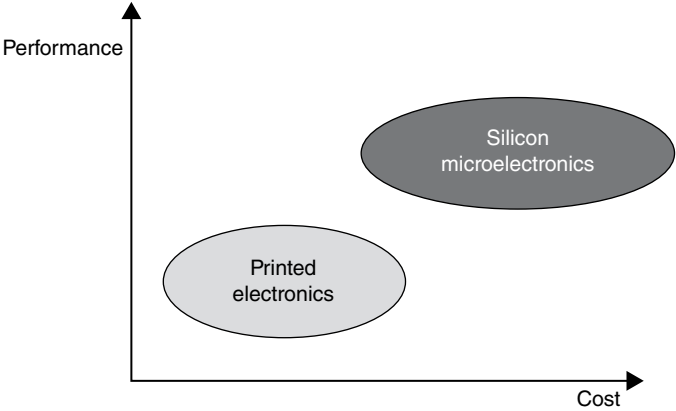


Figure 1.8 Printed electronics vs. silicon microelectronics

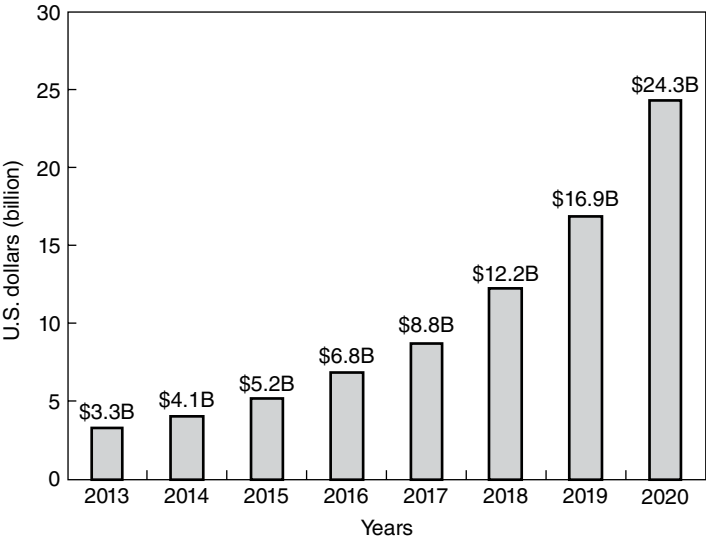


Figure 1.9 Market forecast for printed electronics. (Data from IHS market report with permission.)

It is those unique features that earn printed electronics a place in the vast electronic application market. Some market research firms have been tracking the growth of printed electronics over the years. For example, IDTechEx, a British market research firm, started charting and forecasting the market growth of printed, organic, and flexible electronics in 2008. Their latest market report showed the combined market for printed, organic, and flexible electronics will be \$80 billion by 2023 [23]. In the combined market, printed electronics will take a 25% share by 2023, which is around \$20 billion. Another market research firm, Display Bank, published their report in June 2013, which specifically targets the printed electronics market, forecasting that the printed electronics market will grow to \$24.3 billion by 2020 [24]. Figure 1.9 is the chart of year-to-year growth from the report.

The forecasted growth rate is not surprising because printed, organic, and flexible electronics are already around us. Samsung and LG, the Korean electronics giants, are already shipping OLED TVs to customers. Panasonic in Japan and AUO in Taiwan have both demonstrated OLED TVs using inkjet printing as one of the manufacturing techniques. Wall size, transparent, and interactive touch-controlled displays are no longer only seen in the movie *Avatar* but commercially available. There will be more of these products in the market, as printing enables a large volume of them to be produced at lower cost. With the Internet of Things (IoT) gaining more widespread use, it is estimated the world will need a trillion sensors by 2023 to connect most things around us [25]. Current manufacturing technologies for silicon microelectronics would be prohibitively high cost. Printed electronics could offer an alternative solution to meet the demand for trillion sensors.

Developing printed electronics is important not only because it represents a fast-growing market but also because it represents a paradigm shift in electronic manufacturing. Conventional subtractive manufacturing takes away materials, which involves lithographic patterning and acidic etching. A perfect example is the manufacturing of printed circuit boards (PCBs). A PCB is not made by printing but by lithographic patterning and acidic etching of copper-coated sheets. Acidic etching not only produces highly polluting waste solutions but also wastes 90% of copper material. China is the world's largest producer of PCBs. The price China pays for such a production capacity is the widespread pollution of soil and water. If the additive printing method can partly replace the subtractive etching, not only the pollution and waste of materials can be reduced—the cost of manufacturing also can be lowered because of simplified manufacturing processes. Printing can potentially make finer lines, which can increase the circuit connection density. The concept of green manufacturing is already being heavily promoted in China. Printing is beginning to be used for making RFID antennas, which are traditionally made by acidic etching.

Like 3D printing, which is hotly pursued worldwide, printed electronics can change the face of many conventional electronic manufacturing processes. Some industries already employed printing to replace some existing manufacturing steps; for example, to print color filters in LCD panel manufacturing and to print e-ink in e-paper manufacturing. Panasonic unveiled their printed 55" high definition colored polymer OLED TV in 2013, and AU Optonics Corp. in Taiwan demonstrated their printed 65" OLED TV in 2014 [26], as shown in Figure 1.10. Though still a prototype, it demonstrated that a TV can be manufactured by printing. The silicon solar cell industry already widely uses screen printing for front electrode manufacturing. Other industries are beginning to consider printing as an alternative manufacturing technology.

The importance of printed electronics gained notice in recent years both in the academic community and the electronic industry. The OE-A, which was established in 2004 in Germany and initially focused on organic electronics, has expanded rapidly in recent years because printed electronics is a main area of focus. OE-A now has 223 members across the globe from 31 countries, covering both academic institutions and industries. Scientific publications in the area of printed electronics started to appear in 2003 and increased significantly in the last few years, as shown in Figure 1.5. The similar trend is seen for patent applications, as shown in Figure 1.11 which is the search results from the Derwent Innovation Index database. The search key words are "organic electronics," "plastic electronics," "printed electronics," and "large-area electronics."



Figure 1.10 Inkjet printed 65" OLED TV demonstrated by AU Optonics Corp. (Taiwan) in 2014

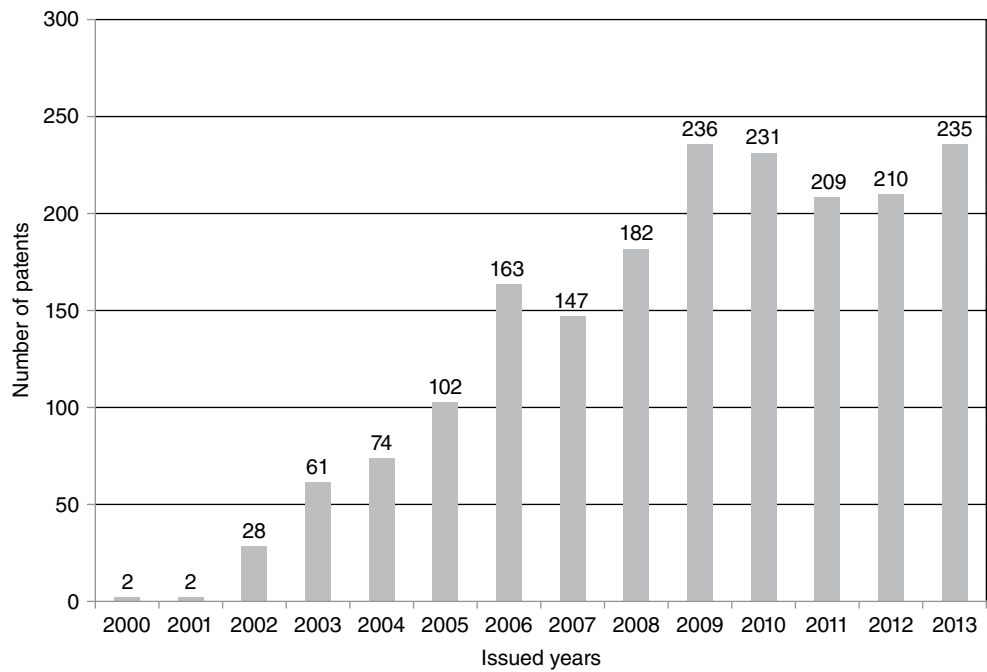


Figure 1.11 Patent applications by years related to organic, large-area, and printed electronics