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Introduction of Printed Electronics and Smart Packaging

1.1 Introduction

Smart packaging is a common solution to improve packaging value and functions, originating from the intersection of multidisciplinary fields and having distinct interdisciplinary characteristics. Smart packaging involves many research directions and application fields, including front-end knowledge of packaging design, and material science, printed technology, wireless communication technology, Internet of Things (IoT) technology, and so forth, as well as the basic knowledge of traditional packaging engineering.

The current research on smart packaging mainly focuses on two aspects: active packaging and smart packaging. The former mainly conveys and monitors information on products with life, such as packaging that uses time–temperature indicators (TTIs) labels. The latter uses various electronic technologies to provide an indication of status or convey other information about the product. Smart packaging has huge potential to improve product safety, quality, and traceability, as well as convenience for consumers.

In recent years, the safety of packaged contents in the logistics process has received extensive attention, especially the logistics and transportation of some valuable products. Monitoring the status of packaged products in the logistics process has become a challenge, and a large number of new technologies have been developed, adopted, and applied to traditional packaging, such as radio frequency identification (RFID) technology, infrared induction technology, global positioning system (GPS), and so forth. But it is noteworthy that these technologies have not been effectively integrated with packaging. Because of this, it is possible to solve these problems if we can combine packaging design and these electronic devices can be directly printed on the surface of packaging products during the graphic information printing process. Using traditional packaging-printing technology to manufacture thin-film electronic devices on packaging will also greatly reduce the production cost of smart packaging and promote its rapid development. As a highly interdisciplinary innovation field, printed electronics (PE) shows great breakthrough potential in promoting the development of ubiquitous electronic products and the innovation of traditional packaging technology [1].

Printed Electronics for Smart Packaging, First Edition. Wei Wu.

1.2 PE Technologies

1.2.1 What Is PE Technologies?

Traditional printing technology is a very mature, fast, and efficient graphic information reproduction technology, and ink plays a very critical factor in it. As early as the 1980s, when organic conductors and organic semiconductor materials were discovered, people saw the hope that future electronic circuits might be fabricated by traditional printing technology. Because organic materials can generally be prepared in solution form, they have the typical characteristics of printing inks. It is hoped that by printing organic conductors and semiconducting inks, transistors in electronic devices can be fabricated and complex electronic systems can be constructed. However, among organic electronic materials, only a large class of organic small molecule materials have good electronic properties, and these organic small molecule materials must be prepared by vacuum evaporation to prepare electronic devices. The charge transport properties (charge mobility) of polymer organic electronic materials suitable for printing are always an order of magnitude worse than those of organic small molecule materials.

In recent years, PE has begun to develop rapidly, mainly because various inorganic micro-/nano-materials have been successfully transformed into functional inks and applied in the field of PE. Inorganic materials also have much higher charge mobilities than organic electronic materials [2–4]. Some inorganic nanomaterials (nanoparticles, nanowires, nanotubes, etc.) can be easily made into inks and then patterned using traditional printing methods [5–7]. The properties of micro-/nano-materials themselves endow these patterns with charge transport, dielectric, or optoelectronic properties to form various semiconductor, optoelectronic, and energy devices.

In this regard, PE becomes an emerging process technology that applies traditional printing methods to the manufacture of electronic circuits and complex multilayer electronic devices, requiring to formulate different functional materials into printing inks and deposit them onto various flexible or rigid substrates using traditional printing principles.

1.2.2 Why Should PE Technologies Be Developed?

(1) **High throughput and low cost**
The printing area and printing speed of the traditional printing technology are very amazing, and the use of this technology to manufacture electronic devices will significantly reduce the manufacturing cost of the device. For example, gravure printing is a widely used roll-to-roll (R2R) technology that can rapidly manufacture high-resolution printed patterns at speeds of more than 150 m/min (determined by the length of the transmission distance between the printing units of the printing press), and these printed patterns are engraved as a discrete cavity into a rotary printing cylinder. The maximum printing area of screen printing can reach $300\,cm \times 400\,cm$. Therefore, PE technology

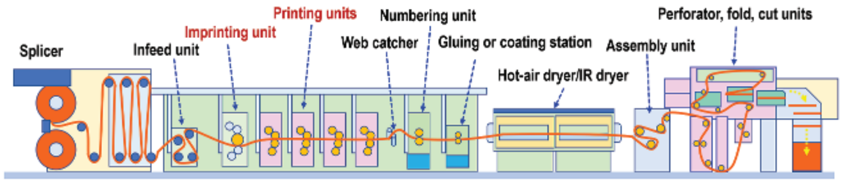

Figure 1.1 Schematic illustration of the printing electronics can be fabricated by roll-to-roll printing press and in-lined with other functional units, such as drying, coating, assembly, folding, and so forth.

can greatly improve production efficiency, simplify production processes, and reduce production costs.

PE technology is directly connected with flexible electronics and R2R technology (Figure 1.1), and the goal is to make various functional electronic devices like those meant for printing newspapers. This is unthinkable for traditional circuit board and complex electronic device manufacturing processes. Moreover, PE substrates are diverse, including plastic, paper, fabric, and so forth. These substrates can be flexibly selected and can also be performed in parallel.

(2) **Additive process**

PE manufacturing is an additive manufacturing process that generally does not require vacuum environmental conditions, but only requires printing functional inks where needed, which is an extremely material-saving manufacturing method [8]. As shown in Figure 1.2, the traditional photolithography involves a complex multistep process, including photoresist coating, mask exposure, development, and chemical etching. During the process, a lot of

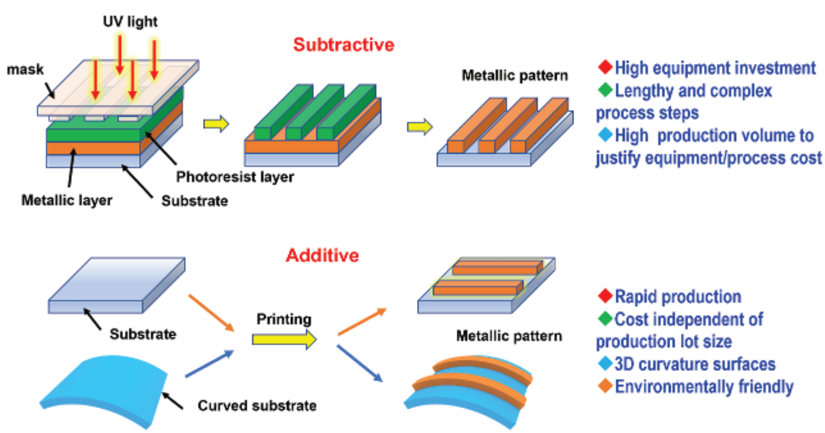

Figure 1.2 The fabrication methods and characteristics of metallic patterns by tradition lithography technology and printed electronic technology.

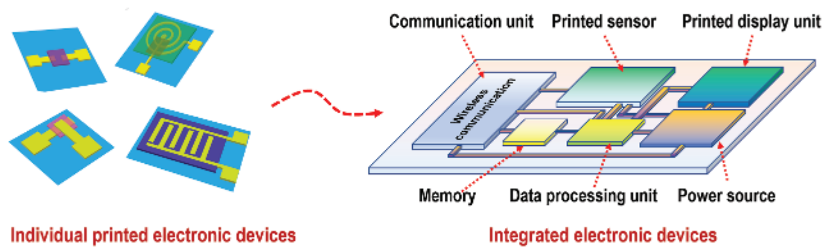

Figure 1.3 Printing methods have been applied to fabricate various types of electronic devices, which can also be directly integrated on flexible substrates by printing methods.

vacuum treatments are involved, which is time-consuming and requires a lot of expensive equipment. It belongs to a technology that first deposits and then removes unnecessary parts. Obviously, PE is a simplified process and material-saving technology. The development of flexible electronic devices is very rapid, and PE can realize circuit and device fabrication on curved substrates, which is also a very big advantage.

(3) **Integration and customization**

The pursuit of foldable and flexible consumer electronic products continues to stimulate innovations in materials and manufacturing technologies. Different functional thin-film electronic devices are integrated on substrates and used to realize various functional applications. These devices also often need to be endowed with higher mechanical durability and stretchability and the ability to measure a variety of complex sensations over large areas. Indeed, many electronic components and interconnect circuits can be integrated and printed, such as sensors, batteries, passive devices, active devices, display units, and the like (Figure 1.3). Recently, some new printable functional materials and manufacturing routes to realize the fabrication of multifunctional electronic skins with mechanical compatibility have been developed, which requires the integration of numerous sensors and data processing and signal transmission electronics [9]. The printing method can be used for the manufacture of customized electronic devices, especially the digital inkjet, for which PE technology will be more convenient.

1.3 Flexible PE Devices

The scale of the consumer electronics market continues to expand, and people's needs and concerns are gradually changing to the bendable and flexible electronic devices. The manufacturing and development of flexible electronic devices have also received a lot of attention, which refer to electronic devices that can still work under a certain range of deformation (bending, folding, torsion, compression, or tension) [10]. Flexible electronics is an emerging electronic technology, which mainly manufactures electronic devices on flexible/stretchable substrates or provides flexible mechanical properties through device structure design. Similar to traditional integrated circuit (IC) technology, the manufacturing process is the driving forces for the development of flexible electronics, and the difficulty is achieving high-throughput, large-area, and low-cost fabrication of small-size electronic devices. Over the past four decades, thin-film flexible electronics in their various forms have underpinned much of the technological innovations in display, sensor, communication, and energy storage and conversion [11].

Texas Instruments invented the IC in 1958, and Intel Corporation invented the world's first commercial microprocessor 4004 in 1971. The two major technologies have promoted the rapid development of information technology, and microelectronics has always followed Moore's Law. Over the past half century, the scale of integration of microelectronic chips has grown by more than a billion times. In 2021, Apple released the new A15 bionic processor, which uses Taiwan Semiconductor Manufacturing Company, Ltd (TSMC)'s 5 nm process and integrates nearly 15 billion transistors. The core of microelectronics technology lies in the manufacture of chips. Microelectronic chips are ubiquitous in our lives, and it is this tiny but extremely important device that makes people's lives more and more intelligent and convenient. However, the traditional microelectronics technology manufacturing process is complicated and generally requires the selection of high-purity rigid substrates and harsh vacuum environments, making it difficult to realize the manufacture of flexible electronic devices.

The development of flexible electronics is one of the main directions of modern electronic information technology, and the form of some traditional electronic devices will also be completely changed, which will also lead to a change in the rigid impression of human beings on electronic products. For example, foldable, rollable, and flexible displays will change the presentation form of existing pictures and movies and make consumer electronic products such as mobile phones and TVs more novel and lightweight. The demand for flexible and wearable electronic products is very strong in the field of consumer electronics and customized medical care (Figure 1.4), and achieving low-cost manufacturing of flexible electronic products becomes the key. In this case, PE is a strong candidate due to its own smart manufacturing and low-cost attributes. The development of PE technology is not to replace traditional microelectronics technology, but to complement it, and can play a role in flexible electronics technology, wearable electronics technology, and smart packaging.

In recent years, the development of artificial intelligence technology has promoted the precision, intelligence, and efficiency of speech recognition, mechanical control, and economic policy decision-making. Flexible electronics is the basic support of artificial intelligence and will lead and expand the application of artificial intelligence technology in more fields. Flexible electronics have the advantages of thinness, lower power consumption, better biocompatibility, and tunable mechanical performance. The constructed health monitoring device can generally be applied to the joints where the human body often moves and does not affect sports and daily life. Smart wearable devices can wirelessly connect application software and

Figure 1.4 Conceptual diagram of the application of wearable electronics in smart sensing technologies, human–machine interfaces and health monitoring, interconnecting daily activities with facilities, devices, and mobile terminals. Source: [12]/John Wiley & Sons/CC BY 4.0.

networks to realize the combination of remote office and leisure and can also realize mind control technology based on physiological electrical monitoring, IoTs, and artificial intelligence technology. Implantable flexible electronic devices offer new treatments for complex diseases such as Parkinson's, epilepsy, and depression.

Flexible electronics can integrate cutting-edge technologies such as intelligent materials, sensors, information transmission, and processing and improve the intelligence level of related equipment and systems. The use of printing methods is the main way to reduce the manufacturing cost of flexible electronic devices. In-depth research in the field of flexible PE is a new engine driving comprehensive innovation and development. Printed flexible electronics is a subversive science and technology generated on the basis of a high degree of interdisciplinary integration. It is expected to break through the inherent limitations of classic silicon-based electronics and can be used for the design and integration of devices in the post-Moore era, energy revolution, medical technology reform, and so forth. The development of flexible PE devices become an important strategic opportunity for independent innovation to lead future electronic industrial development.

1.4 PE for Smart Packaging

Exquisite packaging is inseparable from packaging structure design and high-quality printing. Packaging and printing is an important means and approach to increase the added value of commodities, enhance commodity competitiveness, and develop markets. With Heidelberg and KBA, two of the world's largest packaging and printing equipment manufacturers, fully transforming into digital and intelligent direction, it marks that the packaging and printing industry has started a journey to fully enter the era of Industry 4.0. The use of printing methods to manufacture electronic devices on traditional packaging surfaces is expected to bring new functions to packaging and add more value to products. PE manufactures many electronic devices such as printed batteries for powering small systems [13–15], simple digital logic processing circuits for data processing [16–18], and physical or chemical sensors for data acquisition [19–22]. All these electronic devices can construct intelligent system on the surface of tradition packaging. Higher performance can be achieved with printed hybrid electronics [23]. Therefore, smart packaging based on PE technology will bring great changes to many packaging application scenarios.

1.4.1 Food Packaging

Foodborne illnesses are usually contagious or toxic and are caused by bacteria, virus, parasite, or chemicals entering the body through contaminated water or foods [24]. Food packaging safety is an important part of ensuring food safety. In fact, food packaging is an integral part of food manufacturing systems. It protects food from biological, chemical, and physical damage during the circulation process from the factory to the consumer. Food packaging can also have the function of maintaining the stable quality of the food itself, facilitating the eating and identification of food, attracting the image of consumption, and having value other than material cost. To a large extent, food packaging has become an integral part of food, which will directly or indirectly affect food quality [25]. Not only should modern food packaging focus on the development, research, and application of new packaging materials, but it also urgently needs to use PE technology to add higher technological content to promote the development and intelligence of packaging technology.

In addition to the fundamental role of protecting products from unwanted biological, chemical, and physical damage and keeping products clean, smart packaging system has a great potential for enhancing the shelf life and safety of food products [27]. As shown in Figure 1.5, the use of PE technology to manufacture smart tags with sensors and apply them to food packaging can greatly improve food safety monitoring and early warning capabilities. There are three types of smart labels (smart indicators, sensor-based labels and intelligent tags), one of which is a label with diagnostic or detection functions, mainly including TTIs, freshness indicators, oxygen indicators, carbon dioxide indicators, packaging leakage labels, and so forth. Various sensor-based labels have also been developed and used in food packaging, including oxygen sensors, gas sensors, biosensors, and the like. The core difference between sensors and indicators lies in their detection capabilities: sensors

Figure 1.5 Smart tag for monitoring of foods. (a) Inkjet-printed multisensory platform. (b) A smart temperature-sensing label consisting of memory, display, and wireless communication unit. Source: [26]/with permission of John Wiley & Sons.

can accurately and quantitatively detect the target analyte in the package based on the response signal, while indicators only have qualitative or semi-quantitative analysis functions, which are mainly used to determine the presence or absence of the target analyte or the approximate concentration range. The intelligent tags often use the information technology, mainly including radio frequency identification tags (RFID), antitheft electronic surveillance tags, electromagnetic identification tags, and so forth. But in fact, these types of label technologies can be mixed through the design of the label structure and function, which further promotes the interaction of packaging safety information.

1.4.2 Drug Packaging

Pharmaceutical packaging is an integral part of medicines and has a significant impact on the quality and safety of medicines. In recent years, with the diversification of drug types, the form of pharmaceutical packaging has also changed from single to diversified. The emphasis on drug quality and safety has been continuously strengthened, the supervision has become increasingly strict, and pharmaceutical packaging enterprises are facing greater challenges. Drug packaging is supposed to provide information to doctors, pharmacies, and patients, and the amount of information is growing. In addition to the information that must be provided by laws and regulations, users also want to receive information to help them take their medicines correctly.

As shown in Figure 1.6, with wireless technologies such as RFID/NFC and Bluetooth, new communication channels can be established with patients while their behavioral data are analyzed. Thus, smart pharmaceutical packaging can realize some important interactions, such as reminding them of their upcoming medication schedules and providing important reminders for medication [28]. Doctors can also use the app to inform patients about their personal doses and easily adjust those doses when their health improves, avoiding the drug-overdose epidemic. Prototypes of drug packages with integrated e-paper display already exist [29]. Through display devices and acoustic and visual signals integrated on the drug packaging, drug packaging can convey information such as reminding patients to take their medicines in time and purchase new medicines in time.

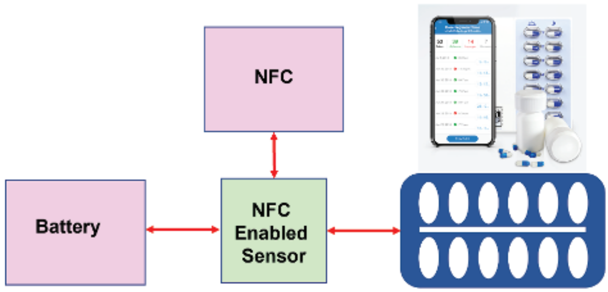

Figure 1.6 Schematic illustration of smart blister packaging.

Smart pharmaceutical packaging can also avoid drug sorting errors to the greatest extent and has great advantages in drug storage and sorting in large medical institutions [30]. Obviously, these electronic components can be manufactured by PE technologies, and low-cost smart packaging systems can play a huge role in monitoring drug dosage and serve for smart medical applications.

1.4.3 Smart Logistics and Supply Chain

Problems such as ensuring the authenticity and reliability of packaged products, ensuring whether the cold chain packaging products are really in a suitable environment during the entire process of transportation, and ensuring that the checked baggage in airport is no longer lost have opened up a lot of new opportunities for PE products and possibility. As shown in Figure 1.7, low-cost labels based on PE methods that can track goods in real time and enable verification of agreed transport parameters at any time also have huge benefits for building smart supply chains [31]. Intelligent packaging based on the IoTs and cloud computing has

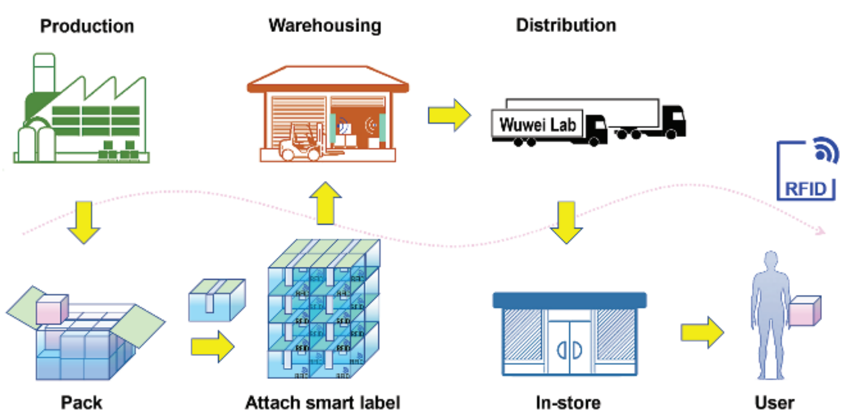

Figure 1.7 Schematic illustration of application radio frequency identification tag technologies in supply chain enables error-free, real-time efficiency and visibility throughout your operations (end-to-end asset visibility and authentication).

become the goal and direction of the development of intelligent logistics [32, 33]. In the logistics process, many carton packages are generally discarded after the goods are delivered, but as the amount and cost of carton boxes increase year by year, this method is neither environmentally friendly nor economical. In recent years, many food retailers and manufacturers have asked to switch to plastic recyclable pallets or boxes as a way to be environmentally friendly and reduce costs. Nonetheless, customer demands face new challenges, such as pallets that are often not recycled efficiently or pallets that are transferred to third parties to prove ownership. If smart labels are applied to these fields, these problems will also be solved.

With the rapid development of e-commerce, online shopping is becoming more and more popular, resulting in massive express packaging. Express service connects hundreds of industries and thousands of households and is an indispensable part of modern production and life. The number of express parcels worldwide has exceeded 100 billion. This has made the express delivery a labor-intensive industry, many of which are repetitive actions, such as the sorter of a delivery company scanning barcodes. In fact, traditional express barcodes can be completely replaced by smart labels. For example, smart labels are attached to the express package of a container. When passing through the transfer station, the data information on the label can be automatically sent to the data concentrator. As long as these data information is further transmitted to the automation equipment with set parameters, the scanning device can automatically identify the properties and destination of the goods, and the sorting equipment can work without scanning the codes one by one.

1.5 Content and Structure of This Book

The mission of PE is to serve the development of flexible electronics in the electronic information industry, and it is oriented to the research on the frontier basic issues of flexible electronics in organic display, energy devices, life and health, and national defense and military industries. PE involves printing engineering, electronic and information technology, materials science, and the like. The intersection of knowledge fields covers the knowledge system of key materials of PE, processing technology, flexible electronic devices, and so forth.

This book is divided into nine chapters in all. In terms of content, each chapter is relatively independent, but also has a certain logical connection, as shown in Figure 1.8. Chapter 1 clarifies the definition of PE, why PE should be developed, and how PE can be applied in smart packaging. Chapter 2 mainly demonstrates the definition and existence forms of intelligent packaging, why it is necessary to develop intelligent packaging, and the main means and trends of intelligent packaging development. Chapters 3 and 4 focus on the most conventional PE manufacturing methods and functional inks and substrate materials used in PE and smart packaging, focusing on how printing methods can be used to enable the manufacture of electronic devices and integrate with smart packaging. Before realizing the fabrication of electronic devices, electrodes, tracks, and circuits are the basic elements that make up electronic devices, and Chapter 5 will provide an overview

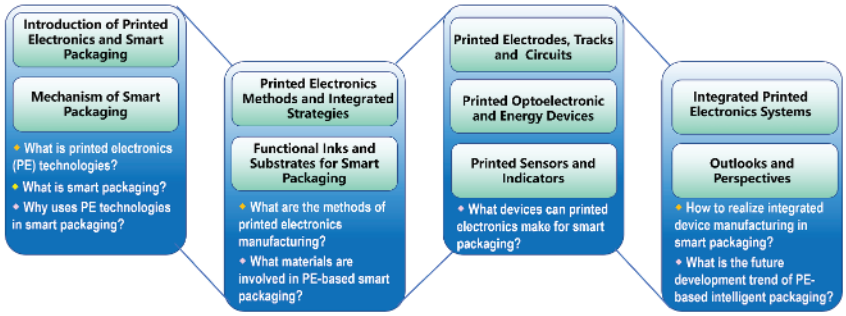

Figure 1.8 Schematic illustration of the main contents and structure of this book.

of these basic elements in conjunction with some common PE devices in smart packaging. Chapters 6 and 7 will focus on PE devices commonly found in smart packaging and describe how printing methods can be used to fabricate devices, including optoelectronics, sensors, indicators, and power-supplying devices. In the practical application of smart packaging, different types of PE devices will be integrated onto the surface of packaging materials or attached to the packaging in the form of smart labels/tags, all of which need to realize the construction of integrated printed electronic systems (IPES). Chapter 8 will focus on demonstrating the recent progress of IPES. In Chapter 9, a systematic summary of the book will be provided and an outlook on the development trends of PE technology involved in smart packaging will be discussed.

References

1 Bonnassieux, Y., Brabec, C.J., Cao, Y. et al. (2021). *Flexible and Printed Electronics* 6: 023001.
2 Garlapati, S.K., Divya, M., Breitung, B. et al. (2018). *Advanced Materials* 30: 1707600.
3 Cano-Raya, C., Denchev, Z.Z., Cruz, S.F., and Viana, J.C. (2019). *Applied Materials Today* 15: 416–430.
4 Choi, Y., Seong, K.-d., and Piao, Y. (2019). *Advanced Materials Interfaces* 6: 1901002.
5 Yao, W.J., Tian, Q.Y., and Wu, W. (2019). *Advanced Optical Materials* 7: 1801171.
6 Douglas, S.P., Mrig, S., and Knapp, C.E. (2021). *Chemistry – A European Journal* 27: 8062–8081.
7 Huang, Q. and Zhu, Y. (2019). *Advanced Materials Technologies* 4: 1800546.
8 Wu, W. (2017). *Nanoscale* 9: 7342–7372.
9 Chortos, A., Liu, J., and Bao, Z. (2016). *Nature Materials* 15: 937–950.
10 Wu, W. (2019). *Science and Technology of Advanced Materials* 20: 187–224.
11 Nathan, A., Ahnood, A., Cole, M.T. et al. (2012). *Proceedings of the IEEE* 100: 1486–1517.

12 Li, J.-a., Ma, Z., Wang, H.-t. et al. (2019). *Advanced Intelligent Systems* 1: 1900063.

13 Liang, J., Tian, B., Li, S.Q. et al. (2020). *Advanced Energy Materials* 10: 2000022.

14 Liang, J., Jiang, C.Z., and Wu, W. (2019). *Nanoscale* 11: 7041–7061.

15 Liang, J., Jiang, C., and Wu, W. (2021). *Applied Physics Reviews* 8: 021319.

16 Sou, A., Jung, S., Gili, E. et al. (2014). *Organic Electronics* 15: 3111–3119.

17 Kwon, J., Takeda, Y., Fukuda, K. et al. (2016). *Advanced Electronic Materials* 2: 1600046.

18 Fukuda, K. and Someya, T. (2017). *Advanced Materials* 29: 1602736.

19 Tian, B., Yao, W.J., Zeng, P. et al. (2019). *Journal of Materials Chemistry C* 7: 809–818.

20 Luo, C.S., Tian, B., Liu, Q. et al. (2020). *Advanced Materials Technologies* 5: 1900925.

21 Ge, L., Ye, X., Chen, B. et al. (2021). *Flexible and Printed Electronics* 6: 015013.

22 Khan, S., Ali, S., and Bermak, A. (2019). *Sensors* 19: 1230.

23 Street, R.A., Ng, T.N., Schwartz, D.E. et al. (2015). *Proceedings of the IEEE* 103: 607–618.

24 Kalyoussef, S. and Feja, K.N. (2014). *Advances in Pediatrics* 61: 287–312.

25 Han, J.-W., Ruiz-Garcia, L., Qian, J.-P., and Yang, X.-T. (2018). *Comprehensive Reviews in Food Science and Food Safety* 17: 860–877.

26 Khan, Y., Thielens, A., Muin, S. et al. (2020). *Advanced Materials* 32: 1905279.

27 Ahmed, I., Lin, H., Zou, L. et al. (2018). *Packaging Technology and Science* 31: 449–471.

28 Selamneni, V., Barya, P., Deshpande, N., and Sahatiya, P. (2019). *IEEE Sensors Journal* 19: 11255–11261.

29 https://www.faller-packaging.com/en/innovations-and-solutions/smart-packaging/smart-packaging-solutions.

30 Graddage, N., Ding, H., Py, C. et al. (2016). *IEEE Transactions on Components, Packaging and Manufacturing Technology* 6: 335–345.

31 Pal, A. and Kant, K. (2019). *IEEE Access* 7: 17675–17695.

32 Tang, X. (2020). *IEEE Access* 8: 151150–151159.

33 Song, Y., Yu, F.R., Zhou, L. et al. (2021). *IEEE Internet of Things Journal* 8: 4250–4274.