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Introduction

1.1 Connected Smart World

Along with the revolution of information and communication technology (ICT) over the past decades, people have been connected to the Internet by billions of computers and mobile phones. Now this revolution is extending the connections to the physical world (things and objects), namely Internet of Things (IoT), a vision of the connected smart world [1, 2]. It has been recognized as the third wave of the ICT industry, after the computer in the 1940s and the Internet in the 1970s. The IoT conceptually represents the future ICT world, which is often associated with such terms as “ambient intelligence,” “ubiquitous computing,” and “pervasive,” as illustrated in Figure 1.1. Its development depends on dynamic technology evolutions in a set of multidisciplinary and interdisciplinary fields, ranging from the material and device, sensor and integration technology, to wireless communications and networking. Related technical innovations will leverage a number of emerging applications and services, which may change our lifestyle as dramatically as what has occurred since the introduction of the Internet 20 years ago.

The IoT enables a wide range of applications and new business opportunities in many areas including medical and healthcare, safety and security, logistics and inventory management, manufacturing, and automation. Healthcare and intelligent logistics represent the most rapidly expanding areas where smart devices and systems can either be implanted into human or animal bodies to monitor health information or be hidden, for example, in a piece of biopaper worn on the human body or on a pharmaceutical/food package. Examples of such systems are temperature and bacteria monitoring, smart labels for food packaging, miniaturized wireless respiration monitoring devices for healthcare, radio frequency identification (RFID) systems integrated with biochemical monitoring devices for intelligent pharmaceutical packaging and storage, and large-area embedded bio-patches on flex-foil for health monitoring and analysis with radio communication links [3].

The IoT consists of billions of everyday objects that are being connected and smart, such as food and pharmaceutical packages, furniture, machines, wearable devices, and more. Ericsson and Cisco projected that there would be 50 billion Internet-connected devices by 2020, which is one order of magnitude

Smart Electronic Systems: Heterogeneous Integration of Silicon and Printed Electronics,
First Edition. Li-Rong Zheng, Hannu Tenhunen, and Zhuo Zou.

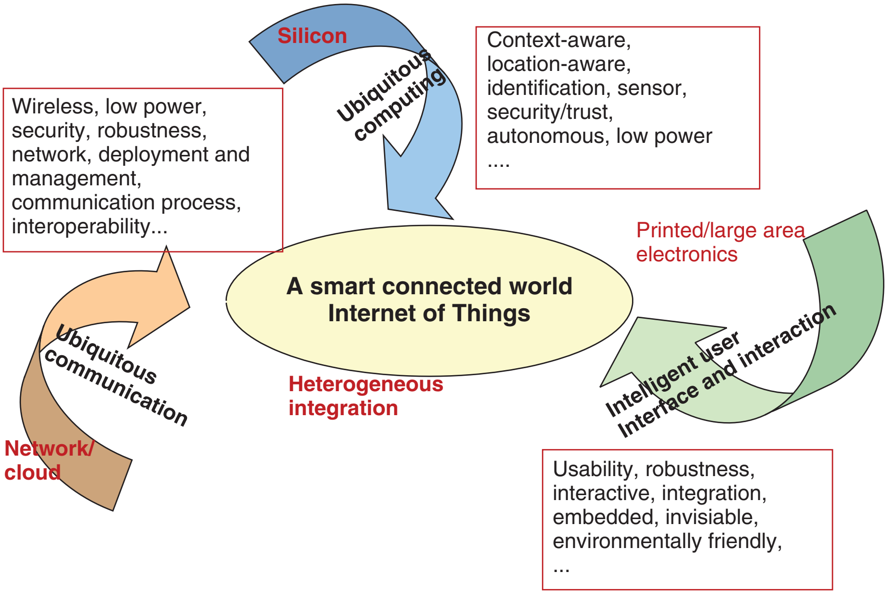

Figure 1.1 Technologies and applications of connected smart world and the Internet of Things.

greater than the 5 billion PCs and mobile phones that can be connected to the Web today (https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide). Such smart objects can monitor their status and the surrounding environment, as well as their geographic location. They are bridged through micropower wireless links to existing ICT infrastructures with unique identification numbers or IP addresses, allowing connections between the virtual world of the Internet and the physical world of things.

1.2 Smart Electronic Systems

Smart systems (SSs) usually combine cognitive functions with sensing, actuation, data communication, and energy management in an integrated way to provide safe and reliable autonomous operation under all relevant circumstances. Depending on the degree of autonomy, smart systems are categorized into three generations [4].

- First generation smart systems integrate sensing and/or actuation as well as signal processing to enable actions.
- Second generation smart systems are built on multifunctional perception and are predictive and adaptive systems with self-test capabilities that are able to match critical environments. Moreover, they are equipped with network facilities and advanced energy scavenging and management capabilities
- Third generation smart systems perform human-like perception and autonomy, and are able to generate energy.

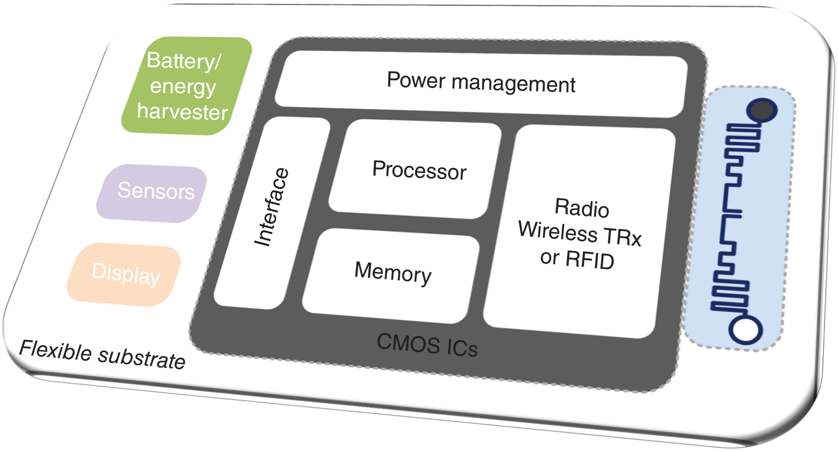

Figure 1.2 Architecture and main building blocks of a smart electronic system.

Smartness or intelligence presented above is essentially realized by *Smart Electronic Systems* seamlessly integrated with everyday objects that can be physically flexible. Such systems usually incorporate functions of sensing/actuating, computing/perception, and communication and networking. A generic architecture along with typical building blocks of a smart electronic system is illustrated in Figure 1.2. It consists of an embedded processor and memories, a radio for wireless networking, energy harvesting, and storage, sensors/actuators, and interface circuits that interact with the environment or people. Thanks to the heterogeneous nature, the development of smart electronic systems requires joint efforts in two dimensions as depicted in Figure 1.3: (i) evolution of the semiconductor technology driven by Moore's law and beyond ("More Moore"); (ii) multifunctionality and diversity that are enabled by emerging technologies with different materials and devices, the so-called "More-than-Moore" [5]. On the one hand, integrated circuits (ICs) have been scaling along the trend of "More Moore" toward sub-10 nm, offering increased density and lower power consumption with reduction in cost per transistor and cost per function [6]. On the other hand, interfacing to the real world and to the human body and senses requires that electronics or other functional devices are distributed over a large surface area. There is therefore a great demand for electronic devices and systems on the macroscale, the so-called macroelectronics [7] or large-area electronics (LAEs) [8], aiming to decrease the cost per area [9]. Initially, the LAE (including printed, flexible, or organic electronics) was driven by area-intensive applications, such as displays and photovoltaics. Then, the application scope has expanded dramatically over recent decades, covering medical, sensing, flexible, and ultrathin consumer devices, pursuing cheaper electronics capable of interacting with the environment on the macroscale [8]. The development of flexible and printed electronics (FPEs) enables the cost-effective manufacture of such devices.

Smart electronic systems are targeted to provide adequate performance, but in a low cost, novel form factor on flexible substrates such as paper or stretchable plastic. Printing as a manufacturing technique is a promising approach to

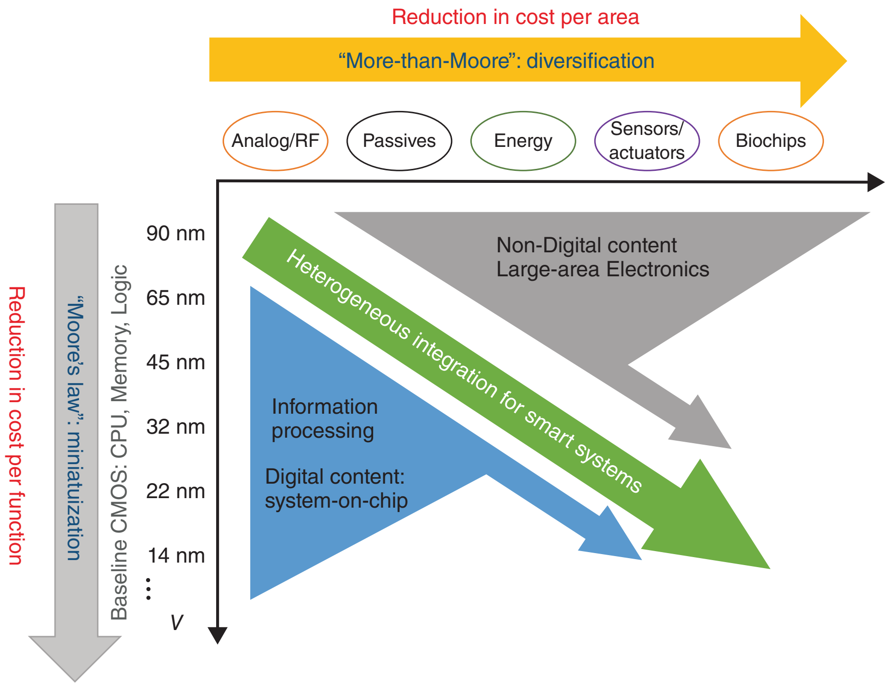

Figure 1.3 Technology roadmap of smart electronic systems in the ear of "More Moore" and "More-than-Moore."

fabricate low-cost, flexible, and LAEs on flexible media, including circuits, sensors, antennas, transducers, and batteries. Compared with silicon-based circuits (more specifically, CMOS ICs), all-printed systems yet suffer from low integration density, long switching time, and high cost per function. For example, the speed and energy efficiency of the state-of-the-art thin-film transistors (TFTs) remain orders of magnitude below the complementary metal-oxide semiconductor (CMOS) technology. Therefore, silicon-based chips performing sophisticated feats such as communication computation and communication are still inevitable. Thus, a heterogeneous integration platform for hybrid systems is in great demand, which employs a cost-effective, large-area manufacturing technique while keeping the same complex functionality and processing capability as silicon-based systems. The complementariness of silicon-based electronics (CMOS) and printed electronics (LAE) are summarized in Table 1.1 [10].

1.3 Overview of the Book

To realize the vision of the IoT toward a truly connected smart world, there are three key enablers in smart electronic system design. (i) Self-powered integrated circuits based on advanced CMOS technology for computing, communication, sensing, and perception; (ii) flexible and LAEs for multifunctionality and interfacing to the analogy; and (iii) hybrid system integration technologies that integrate

Table 1.1 Complementariness of silicon electronics and printed electronics.

	CMOS	**LAE**
Computation	High throughput	Low speed
	High logic density	Low logic density
	Low energy/MHz	
Communication	High data rate	Coupling
	Low energy/bit	Interconnects
		Large-size antenna
Sensing	Precision instrumentation	Transducers
	Analog-information convertors	Large substrates
Power	DC–DC/AC–DC conversion	Energy harvester
	Regulators	Printed battery
	Adaptive management	

conventional silicon-based CMOS chips with printed materials/devices on flexible substrates. This book covers various aspects of smart electronic systems and summarizes our recent research from materials, devices, and systems to applications, with special focus on LAEs using printing techniques and integration technologies for hybrid flexible systems.

Figure 1.4 navigates the content of the book. To start with, Chapter 2 provides the fundamentals of printing techniques and functional inks. It gives a comprehensive overview on conductive and semiconductor inks such as carbon nanotubes (CNTs)-based electronic inks. Chapter 3 investigates TFT technologies, especially those with single-walled carbon nanotubes (SWCNTs) networks as the semiconducting channels. We introduce and compare the development of printed TFTs based on different semiconductor inks such as organic

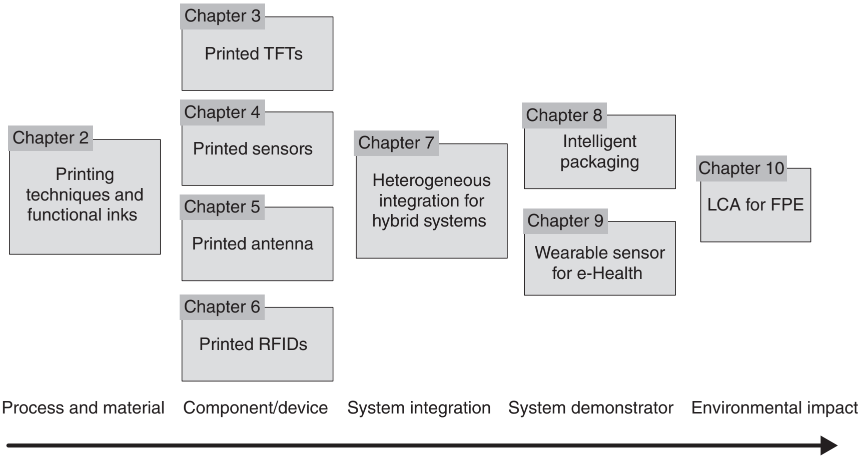

Figure 1.4 Navigation of the book.

semiconductors, metal oxides and SWCNTs. Chapter 4 introduces printed sensors using CNTs. Detailed discussions are provided on humidity sensing properties of functionalized multiwalled carbon nanotubes (f-MWCNTs). By integrating the f-MWCNT resistors, two fully printable and flexible passive humidity sensors with chipless RFID tags are demonstrated using ultra-high frequency (UHF) RFID backscattering and ultra-wideband (UWB) time-domain replications, respectively. Chapters 5 and 6 focus on printed RFID, which has been recognized as one of the fundamental communication mechanisms for smart objects. Design and manufacture issues of printed RFID antennas are studied in Chapter 5, while Chapter 6 introduces the printed chipless RFID technology that can eliminate the need for an IC chip. Time-domain and frequency-based chipless RFID tags are presented, respectively. As was discussed, it is still necessary to combine LAEs with CMOS, within hybrid systems; therefore in Chapter 7, we take a close look at heterogeneous integration of silicon and printed electronics. The chapter focuses on chip-to-flex interconnects by inkjet printing and the integration process, as well as the electrical characteristics and performance reliability. Then a heterogeneous integration platform enabled by inkjet printing is presented. The platform is applied to two representative applications, which are demonstrated in Chapters 8 and 9, respectively. The example of intelligent packaging for fresh food tracking is presented in Chapter 8. A silicon microcontroller and light-emitting diodes (LEDs) are integrated with printed conductive pattern and humidity sensor on flexible substrates. Chapter 9 presents a wearable sensing device incorporating a system-on-chip and inkjet-printed electrodes for e-Healthcare monitoring. Finally, we briefly introduce the environmental impacts with case studies of life impact assessment of the flexible and printed electronics.

References

1 (2007). When everything connects. *The Economist, Volume 383, Issue 8526, London*, https://www.economist.com/node/9080024.

2 Porter, M.E. and Heppelmann, J.E. (2014). How smart, connected products are transforming competition. *Harvard Business Review* 92 (11): 64–88.

3 Zheng, L.R., Nejad, M.B., Zou, Z. et al. (2008). Future RFID and wireless sensors for ubiquitous intelligence. *2008 NORCHIP*. IEEE: Tallinn, pp. 142–149. doi: 10.1109/NORCHP.2008.4738269.

4 EPoSS Industry Association (2014). *Smart systems in the multi-annual strategic research and innovation agenda of the JTI ECSEL, Part D.*

5 Wilson, L. (2013). *International Technology Roadmap for Semiconductors (ITRS).* Semiconductor Industry Association.

6 Vandebroek, S.V. (2016). Three pillars enabling the Internet of everything: smart everyday objects, information-centric networks, and automated real-time insights. IEEE International Solid-State Circuits Conference (ISSCC). IEEE, pp. 14–20.

7 Reuss, R.H., Chalamala, B.R., Moussessian, A. et al. (2005). Macroelectronics: perspectives on technology and applications. *Proceedings of the IEEE* 93 (7): 1239–1256.

8 Arias, A.C., MacKenzie, J.D., McCulloch, I. et al. (2010). Materials and applications for large area electronics: solution-based approaches. *Chem. Rev.* 110 (1): 3–24.

9 Perelaer, J., Smith, P.J., Mager, D. et al. (2010). Printed electronics: the challenges involved in printing devices, interconnects, and contacts based on inorganic materials. *Journal of Materials Chemistry* 20 (39): 8446–8453.

10 Verma, N., Hu, Y., Huang, L. et al. (2015). Enabling scalable hybrid systems: architectures for exploiting large-area electronics in applications. *Proceedings of the IEEE* 103 (4): 690–712.