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INTRODUCTION

1.1 TRACKING ID TECHNOLOGY

A feature of modern society is the increasing use of machine-reading techniques in everyday life. From recording commercial transactions to monitoring logistics, machine reading is increasingly pervasive and important in the modern economy. Although a variety of different technologies have been used, today two technologies are competing for dominance: (i) barcodes and (ii) radio-frequency identification (RFID). Figure 1.1 shows how tracking and tracing ID technology in industry has evolved significantly from the first self-adhesive label manufactured in the 1930s. In the following sections, each of the technologies is discussed.

1.1.1 Barcoding

Barcode identification is a line-of-sight technology that involves scanning a printed pattern comprising light and dark (mark and space) elements with a laser-reader apparatus. The laser beam is either reflected or absorbed by the elements, with the resulting pattern being detected by the reader and converted into digital data according to a conversion protocol. Barcoding was first commercially used in 1974. Today, billions of barcodes are printed yearly for numerous applications related to product tracking, management, and logistics [1].

The key advantage barcodes provide is their information density and low cost; they can be printed for fractions of a cent each. Barcode technology, nevertheless, has important disadvantages. The line-of-sight (LOS) requirement means that a human operator must usually be present to direct the reading process, or at least verify it.

Chipless RFID Sensors, First Edition. Nemai Chandra Karmakar, Emran Md Amin and Jhantu Kumar Saha.

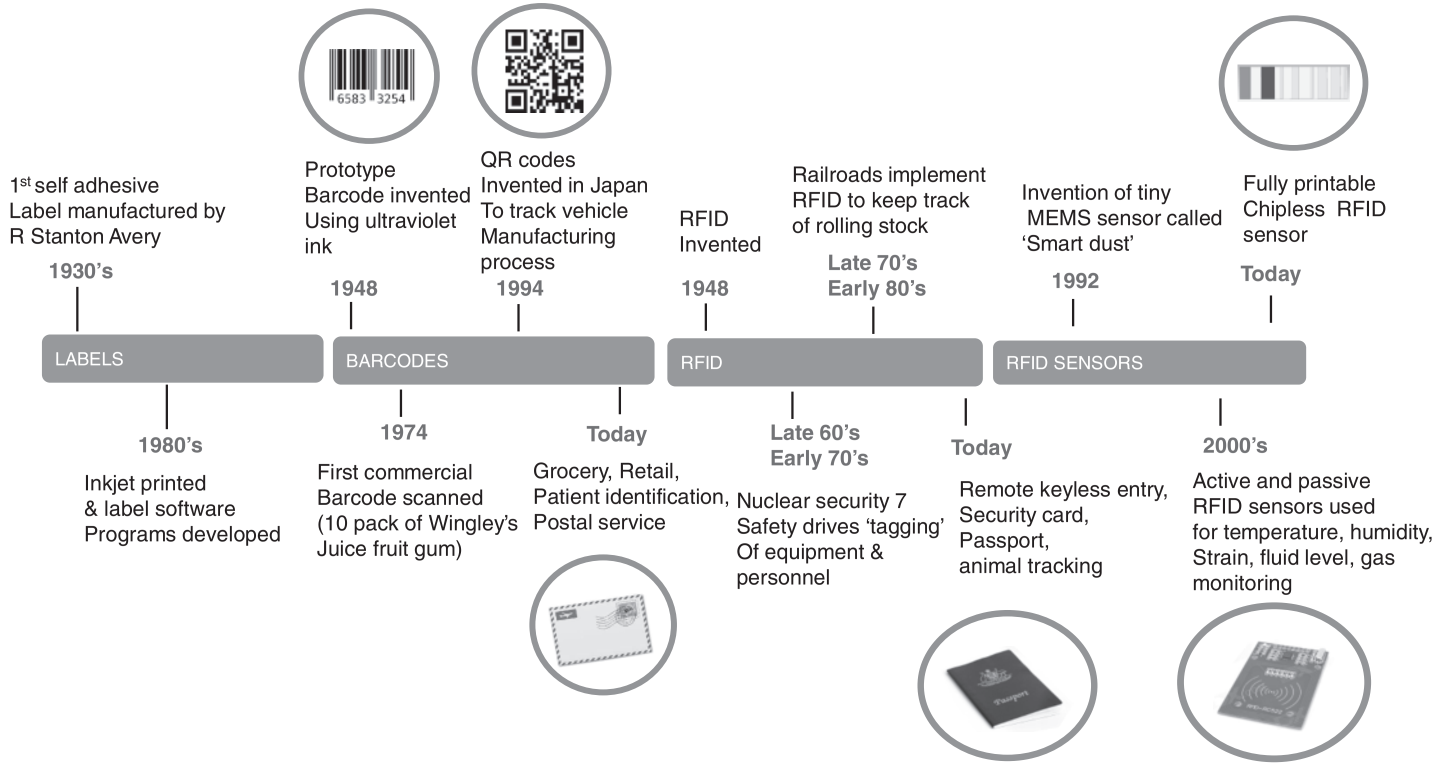

Figure 1.1 Evolution of tracking ID technology

Scanning is usually limited to a single item at a time, making it a slow process compared to purely electronic systems.

1.1.2 Radio-Frequency Identification

RFID technology usually consists of three components: (i) a small and mobile tag unit (or transponder) that is attached to items of interest and (ii) a reader (or transceiver) whose location is generally fixed and which contains (iii) an attached antenna (Figure 1.2). Signals are broadcast by the reader via its attached antenna. The tag receives these signals and responds by either reading or writing the data, or by replying with another signal containing some data, such as an identity code or a measurement value. The tag may also rebroadcast the original signal received from the reader, sometimes with a time delay.

RFID is a rapidly developing revolutionary wireless data collection technology for automatic identification, asset tracking, access control, security surveillance, electronic toll collection, car immobilizers, and smart logistics. The concept of RFID technology germinated in the early 1950s and evolved through the 1980s with the rapid advent of very low-power and application-specific integrated circuits (ASICs). To date, the RFID market has surpassed \$10 billion [2] through its omnipresence in communications and transport, banking systems, retail, distribution logistics, hospital management, and automotive systems. Major retailers such as Wal-Mart in the United States [3] and Coles Myer in Australia [4] are increasingly using RFID and have reduced their reliance on optical barcodes in their businesses. However, RFID has not fully replaced barcodes due to the high tag price. While optical barcodes can be directly printed on packed items with almost no extra cost, RFID tags need special procedures for application to items. However, for expensive items, this cost barrier is mitigated by the extra benefits and flexibility in operation the RFID provides. For example, Gillette has tagged razors costing over \$20 with high-frequency (HF) tags. Optical barcodes have many limitations: (i) they need LOS reading, (ii) barcodes cannot be read in sunlight and dark, (iii) soiled tags cannot be read, and finally, (iv) barcodes have low data capacity. In contrast, RFIDs can be read non-LOS without any human intervention and item-level tagging is possible due to their immense data capacity. For most logistical purposes such as supply chain management in the

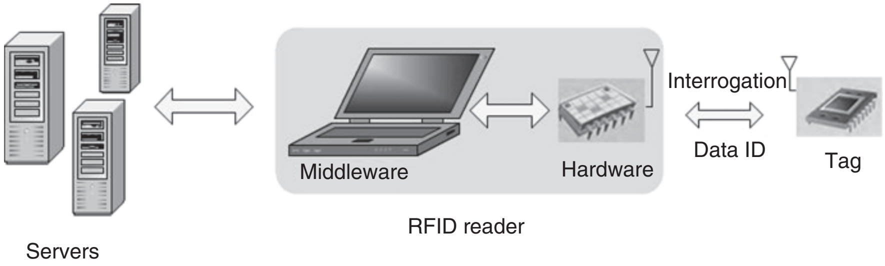

Figure 1.2 Block diagram of generic RFID system

retail sector, RFID tags must offer at least 1 billion unique permutations (known as addresses). This corresponds to a 30-bit binary code with 2^{30} permutations. The only way to produce such high data bits on an RFID transponder at present is by the incorporation of a silicon chip. The cost of fabricating and affixing such a chip is substantial (>10¢), even when the chip is produced in quantities of billions. A printable, chipless RFID system with multibit capacity is needed to overcome the cost limitation and make RFID competitive with optical barcodes.

1.1.3 Chipless RFID

The chipless RFID tag is a breakthrough in overcoming the limitations of conventional RFID technology as it removes the cost associated with the silicon IC chip in the tag circuit. Moreover, the tag is fully printable and passive and is thus resistant to extremely harsh environments and weather conditions. Chipless RFID tags can even be printed on metals and bottles containing liquids [5]. The potential advantages of these unique features permit chipless RFID in unique applications that could not be achieved previously with both barcodes and chipped RFIDs. Some examples include low-cost item tagging such as for banknotes, ID cards, books, aluminum cans, drink bottles, and consumer goods.

1.1.4 Chipless RFID Sensors

Emerging challenges in tracking ID technology demand ubiquitous sensing together with tagging of an object. Figure 1.3 shows the advances in application areas for tracking ID technology over time. Clearly, supply chain management, logistics, transport, and storage of goods have become sophisticated with the advent of the Internet of things (IoT) platform. Here, the primary goal is to connect every object to

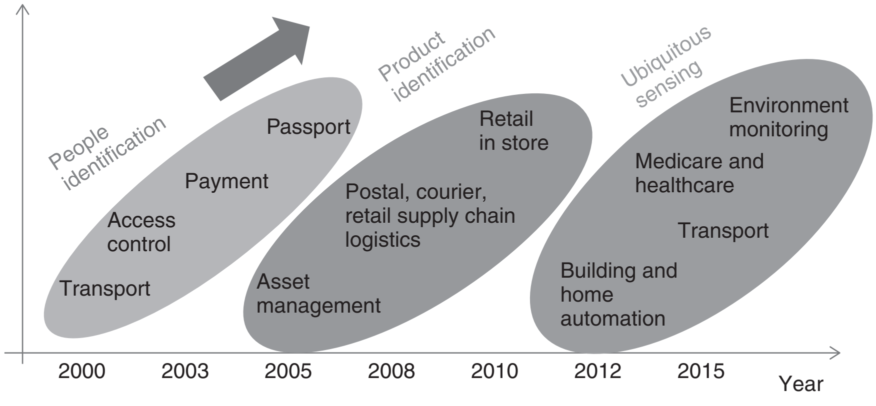

Figure 1.3 Advancement of application areas of tracking ID technology with time

"cloud data" and monitor critical information. However, machine-to-machine communication creates a significant burden on the cost budget of a system due to the high cost of each sensor node.

Alternatively, chipless RFID tag sensors provide identification data and monitor a number of physical parameters of tagged objects without having an active sensor in the tag circuitry [6]. The chipless RFID sensor has benefits over traditional sensors because of its lower cost, longer storage life, robustness, and lower radiated power.

The aim of chipless RFID tags is to replace the existing barcodes used for item-level tagging. The functional evolution of our proposed RFID sensor is shown in Figure 1.4. First, an analogy between the optical barcode (Figure 1.4(a)) and the radar cross section (RCS)-based chipless RFID tag (Figure 1.4(b)) is presented. A chipless RFID tag can be realized by placing conductive and dielectric strips of different shapes adjacent to each other, similar to barcodes [7]. The different combinations of the strips have distinct frequency responses in the backscattered RCS spectrum when interrogated with a polarized *E*-field. This unique response can attribute to encoded data bits in frequency and phase spectrum. However, migrating from optical barcodes to this crude chipless RFID tag has major advantages. The chipless tag has a longer reading range, it is not limited to LOS reading, and, most importantly, it can be used as an anticounterfeiting solution.

Furthermore, a chipless RFID sensor can be realized by modifying one of the metallic/dielectric strips with a smart sensing material (refer to Figure 1.4(c)). The

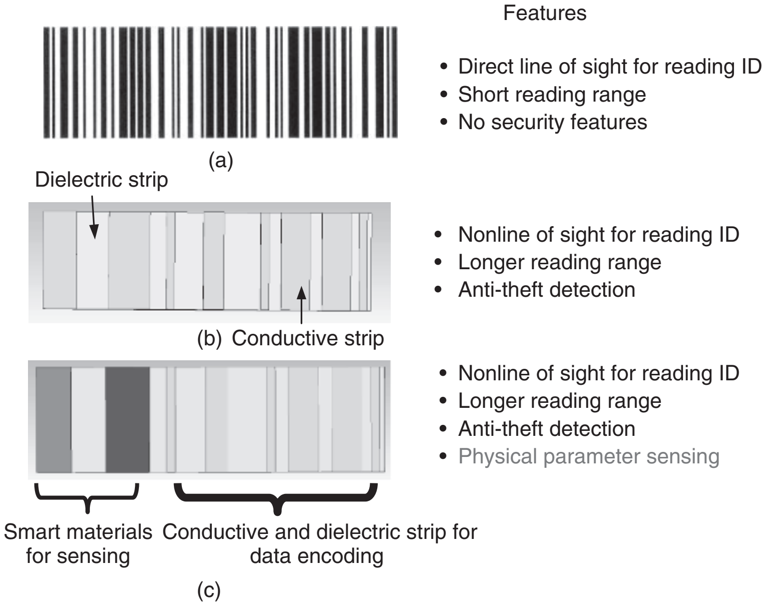

Figure 1.4 Functional evolution and features of tracking ID technology (a) optical barcode, (b) illustration of chipless RFID tag, and (c) illustration of chipless RFID sensor

RCS response of this particular strip corresponds to certain environmental parameters (i.e., humidity, temperature, light, gas, and pH). Hence, a chipless sensor has the features of both data encoding and sensing in a single platform. Moreover, the sensing strips can be modified to include a number of smart materials. Each material responds independently to the change of a particular physical parameter. Here, the data encoding scheme is independent of the sensing mechanism, which entails that multiple parameter sensing is possible in a chipless RFID tag.

1.2 CHIPLESS RFID SENSOR SYSTEM

Our proposed tag sensor consists of a number of RCS backscatterers or resonators that emit a distinct frequency signature when illuminated by an ultra-wide band (UWB) signal. Here an UWB signal is interrogated by a chipless RFID reader (see Figure 1.5).

There are two types of backscatterers within the tag. The first set of scatterers carries the data ID of the tag, and the second set of scatterers carries the sensing information. Here, each scatterer gives a unique spectral response for ID generation and sensing. The resonant frequencies depend on the equivalent circuit parameters of the individual scatterer. In addition, the variation of a particular scatterer's structural parameters does not affect the other resonant frequencies. By tuning the resonant properties of sensing scatterers individually using smart polymer materials, we can develop a single chipless RFID tag with multiple physical parameter-sensing capabilities. The uniqueness of our chipless sensor compared with existing reported studies

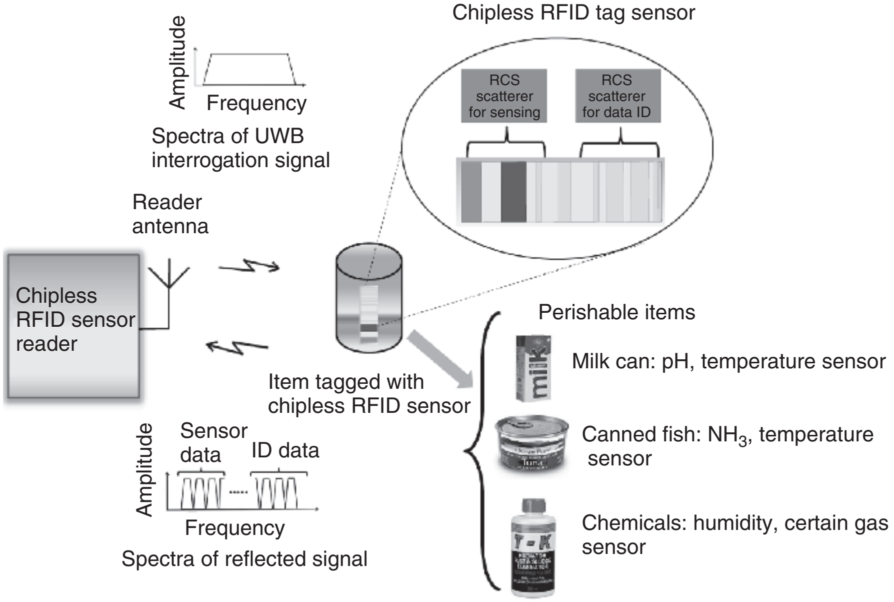

Figure 1.5 Generic block diagram of proposed chipless RFID sensor system

are as follows: (i) data ID and sensing information are coded in both magnitude and phase spectrum, (ii) a single tag has multiple parameter sensing capabilities, and (iii) RF sensing is incorporated using smart materials rather than external sensors or lumped components in the tag circuitry. In addition, the primary application for this chipless RFID sensor is short range (up to 50 cm). Therefore, its application is not affected by UWB power limitation regulation, which entails maximum transmitted equivalent isotropically radiated power (EIRP) of −45 dB m (outdoors) and −55 dB m (indoors) over the UWB microwave frequency band from 3 to 10.6 GHz.

So far, the definition and significance of chipless RFID sensors have been presented. In the next section, the aims of this book and chapter outline are presented.

1.3 PROPOSED CHIPLESS RFID SENSOR

There is a tremendous market push to develop a very low-cost, printable, passive single-node multiparameter chipless RFID sensor for ubiquitous sensing. To address this market demand, an interdisciplinary research project is conducted in two key areas: (i) microwave passive circuit design using metamaterials and (ii) identification, characterization, and fabrication of smart materials for microwave sensing of physical parameters. Integration of smart sensing materials with state-of-the-art passive microwave circuit design provides new fully printable chipless RFID sensors for ubiquitous tagging and sensing of low-cost items. The outcomes are novel high data density and highly sensitive passive RFID sensors, which have numerous real-world applications. Three potential RF sensing applications are addressed in the book: (i) noninvasive radiometric partial discharge (PD) detection and localization, (ii) microwave sensors for environment monitoring, and (iii) nonvolatile microwave memory sensors for event detection. Each application involves the physical layer design of the sensor tag, prototype fabrication, and experimentation. Finally, future research direction is presented in the areas of nanofabrication techniques to make the tag sensor fully printable. Also, a chipless RFID reader architecture is proposed, which is capable of reading data ID and sensing information from the chipless sensor. The book concludes with numerous potential case studies for many emerging applications such as food safety and security, health care, logistics, transportations, smart cities, agriculture, infrastructures, and homeland security.

Figure 1.6 shows an overview of topics covered in the book.

1.4 CHAPTER OVERVIEW

1.4.1 Chapter 1: Introduction

This chapter presents an outline to the overall book on chipless RFID sensors.

1.4.2 Chapter 2: Literature Review

In the first section of this chapter, a comprehensive review of conventional RFID sensors is presented. The objective is to present the classification of RFID sensors

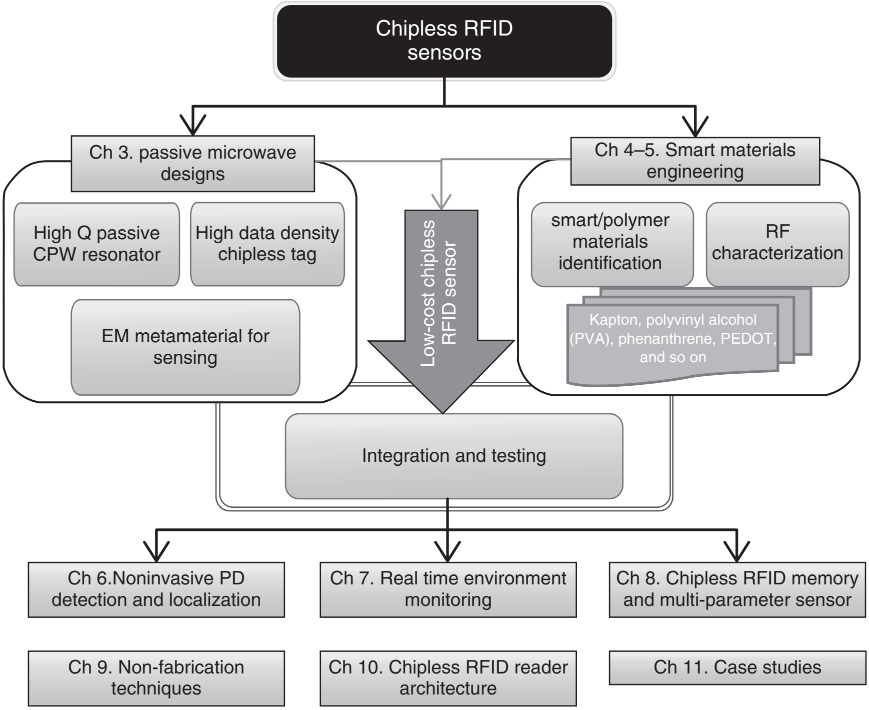

Figure 1.6 Overall research aim and chapter overview

by sensing principle, power requirement, functionality, and applications. This provides a broad overview of the key challenges of current RFID sensor technologies in item-level tagging and sensing.

In the second section, a comprehensive review of state-of-the-art chipless RFID sensors is presented. A comparative summary of various chipless RFID sensor technologies is presented to highlight ongoing research trends. The objective is to establish the aims and challenges in realizing a maintenance-free, batteryless ubiquitous RFID sensor in three application areas considered in this book.

1.4.3 Chapter 3: Passive Microwave Designs

This chapter presents passive RF designs to achieve a compact, high data density, highly sensitive tag sensor for a number of real-world ubiquitous sensing applications. Here, we present three types of passive microwave components: (i) cascaded multiresonator, (ii) RCS backscatterer, and (iii) UWB antenna. A high Q stepped impedance resonator (SIR) is presented for noninvasive radiometric PD detection and localization. A high data density and highly sensitive RCS scatterer is also presented for real-time environment monitoring and event detection. This design includes a slot-loaded patch and an ELC resonator. Here we present the theory, design guidelines, layout, simulation, and measured results for each passive resonator.

1.4.4 Chapter 4: Smart Materials for Chipless RFID Sensors

Smart materials exhibit large and sharp physical and/or chemical changes in response to small physical or chemical stimuli. These materials have great potential for integration with RF devices for environment sensing. This chapter provides a classification of smart materials based on sensing physical parameters (i.e., humidity, temperature, pH, gas, strain, and light). For each class of smart materials, dielectric or conductive property variations in millimeter and microwave frequency are presented. In this chapter, smart materials for microwave sensing application are reviewed and their microwave characteristics in the influence of physical parameters are also explored.

1.4.5 Chapter 5: Characterization of Smart Materials

This chapter presents various novel analysis and characterization techniques including microstructural and surface morphology (X-ray diffraction, XRD; Raman; secondary ion mass spectrometer, SIMS; Fourier-transform infrared reflection, FTIR; atomic force microscopy, AFM; scanning electron microscope, SEM; transmission electron microscopy, TEM; spectroscopic ellipsometry, SE, etc.), optical (UV–vis, SE), electrical and thermal (DC conductivity, stability, etc.), and microwave scattering parameters such as complex permittivity, dielectric loss, and reflection loss in the gigahertz range for sensing materials. This chapter also describes various characterization procedures for dielectric, loss tangent, and conductivity (attenuation) measurement for unknown dielectric and conductive materials. Finally, RF characterization of materials is conducted to investigate their sensitivity and dynamic range.

1.4.6 Chapter 6: Chipless RFID Sensor for Noninvasive PD Detection and Localization

In this chapter, a passive chipless RFID sensor is presented for noninvasive radiometric PD detection in HV equipment. The sensor is a multiresonator-based passive circuit with an antenna for capturing PD signals. The low-cost RF sensor is installed in an individual HV sensing unit for monitoring multiple small units. The sensor block captures the PD signal, processes it with distinct spectral signatures as identification data bits, and transmits the signal to a single sampling channel. From the captured RF signal, both the PD level and source identification can be retrieved. The proposed passive sensor addresses both aspects of PD monitoring, PD detection and faulty source identification. Moreover, in identifying the data bits, time–frequency analysis is utilized for superior detectability. This analysis enables the detection of multiple PD events separated by a defined time delay although they occur at the same instance. Therefore, the sensor can distinguish simultaneous PD occurrences from multiple sources. The proposed sensor system provides low-cost, automated, and battery-free condition monitoring of HV units in a distribution substation.

1.4.7 Chapter 7: Chipless RFID Sensor for Real-Time Environment Monitoring

This chapter presents a chipless RFID sensor for environment monitoring. Two smart materials, Kapton and PVA, are compared for humidity sensitivity in the ultrahigh-frequency (UHF) range. This analysis also determines a number of RF sensing parameters for calibrating humidity in real environments. Next, a chipless RFID humidity sensor is developed and tested for real-time humidity monitoring. Detailed measurement results and sensitivity curves are presented to verify the repeatability and time response of the sensor.

1.4.8 Chapter 8: Chipless RFID Temperature Memory and Multiparameter Sensor

This chapter first presents a chipless RFID memory sensor for temperature threshold detection. This sensor acts as a nonvolatile memory device that is triggered only once. The aim of this memory sensor is to detect and store a particular event when a threshold is exceeded. We use Phenanthrene sublimate material to realize temperature threshold sensing. Detailed experiments are reported to verify the memory effect of our sensor. Finally, a chipless RFID sensor with both humidity and temperature sensing capability is presented.

1.4.9 Chapter 9: Nanofabrication Techniques for Chipless RFID Sensor

This chapter first presents an overview various fabrication techniques that can be used for the development of various chipless RFID sensors. It includes a review on innovative micro- and nanofabrication technologies suitable for roll to roll chipless RFID sensor printing. In addition to the various printing facilities, state-of-the-art micro-/nanofabrication processes, such as hand casting, spin coating, electrodeposition, wet chemical, physical and chemical vapor deposition, laser ablation, direct pattern writing by photolithography/electron beam lithography/ion beam lithography, nanoimprint lithography and etching, and surface and bulk micromachining, suitable for chipless RFID sensor fabrication are described. A general survey and comparison of the different fabrication techniques are also given. The aim is to highlight the limitations of conventional fabrication process and their solutions for on-demand, high-speed printing for flexible, robust, mass productivity of chipless RFID sensors. Moreover, printing, imaging, and characterization procedures of micro- and nanostructures and their integration into RF sensing devices are presented. Printing of microwave passive design on polymers and organic materials has great research potential.

1.4.10 Chapter 10: Chipless RFID Reader Architecture

This chapter details development of a novel chipless RFID reader for decoding chipless RFID sensor's ID information and sensory data. It presents overall architecture of the reader and its operation.

1.4.11 Chapter 11: Case Studies

The chipless RFID sensor has tremendous potential in regard to technological breakthroughs and its social and environmental impacts. It has a number of innovative features such as fully printable, passive, sub-cent, and environment friendly. The potential advantages of these unique features permit chipless RFID sensors in unique applications that could not be achieved previously with both traditional RFID sensors. This section presents a detailed case study on various application areas suitable for chipless RFID sensors. These include retail, pharmaceutical, logistics, power, and construction industries just to name a few.

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