1

Introduction

1.1 Overview

COPYRIGHTED MATERIAL

A sensor is a device which detects or measures a physical, chemical, optical, electrical, and magnetic properties relating to temperature, pressure, strain, molecular finger prints, absorbance, and subsequently records, indicates, or responds to it. The term “solid state” became popular in the beginning of the semiconductor era in the 1960s to distinguish this new technology based on semiconducting materials such as silicon and its doped derivatives, in which the electronic action of such devices occurred within the material, which is in contrast with the vacuum tubes where electronic action occurred in a gaseous state. The solid-state sensor responds to external variations and induces change in properties of the semiconducting material, thereby producing variations in electric current through the semiconducting material. The measure of this electric current is a manifestation of the amount of external variation also called the measurand. However, nowadays with the advent of new materials, technologies, and smart sensor architectures and scopes, the term “solid state” is also used for devices in which the devices have no moving parts. Again, solid-state sensors must not be confused with transducers or actuators which react depending on the sensor response. A solid-state sensor is designed in such a way that the measurand, the physical property to be sensed, exploits a physical phenomenon within the sensor structure. This physical phenomenon if found in traces or is weak may not produce measurable amount of variation in electrical response that can lead to nondetection and poor sensor performance. Such electric signal must be detected by magnifying the weak signals with suitable electronics and signal processing stage. Thus, solid-state sensor with integrated electronics along with other intelligent computational processes is in high commercial demand.

However, the conventional “solid-state” semiconductor-based sensors have transformed largely over the years. With the discovery of new tools and

Solid-State Sensors, First Edition. Ambarish Paul, Mitradip Bhattacharjee, and Ravinder Dahiya.
© 2024 The Institute of Electrical and Electronics Engineers, Inc.
Published 2024 by John Wiley & Sons, Inc.

technologies and the exploration of new materials and synthesis techniques the solid-state sensors have evolved as one of the blooming areas of research because of its promise and the potential to redefine itself. Researchers have developed sensors using metal oxides, ceramics, nanomaterials, polymers, and biomaterials as the active sensing materials on disposable [1], bendable, and ultrathin transparent polymer substrates with no movable parts for different applications [1–8]. Such sensors with no movable parts and capable of generating electronics signals in response to the measurand are considered within the scope of this book. This book discusses the promise, benefits, fabrication techniques, sensing material commonly used, sensor architecture and its role on the performance, sensing strategies, important applications, and new trends for each type of sensors including capacitive, piezoelectric, piezoresistive, optical, chemical, and magnetic. The aim of the book is not only to educate the readers on the scopes and potential of each types of sensors, but also cultivate interest and encourage them to explore new dimensions of multivariant sensing.

1.1.1 Growth in Solid-State Sensor Market

The late twentieth century has witnessed a burst of technological advances in the field of solid-state sensors [9–11]. Industry report suggests that sensors especially solid-state sensors market is expanding its horizon every year [12]. In the present context, this expansion is such that the solid-state sensor market is comparable to leading markets like that of the computers and the communication market. This is because the solid-state sensors are being widely used in every aspect of our lives such as of smartphones, other electronic gadgets, automobiles, security systems, and even everyday objects like coffee makers, sanitizer dispensers, blood pressure monitors, and glucometers. In addition to consumer electronics, these sensors find application in Internet of things (IoT), medical, nuclear, defense, aviation, robotics, artificial intelligence (AI), environment, agriculture, and in geophysical and oceanographic explorations.

The requirement for the solid-state sensing devices have increased considerably over the years (Figure 1.1a) and is also expected to grow subsequently during the decade as predicted in Figure 1.1a, b. This is due to the increasing demand of solid-state sensors in wide cross-section of industrial applications. The demand for cost-efficient, reliable, and high-performance solid-state sensor market is also driving the market growth. There is increased use of solid-state sensors in multiutility devices such as watches and smartphones integrated with sensors, which in turn are assisting the development of solid-state sensor industry. The segmentation of the solid-state sensor market is performed based on classification and application. By classification, the market is divided into varied type of sensors and the respective market revenue per year is shown in Table 1.1. Based on application, the market is divided into automotive, oil and gas, consumer electronics, medical, health care, and others. In addition, the pressure and temperature sensor market were valued at \$7.21 and \$4.99 billion in 2016 and is projected to reach \$12.07 and 6.86 billion by 2024, growing with a CAGR of 6.7% and 4.5%, respectively, during the forecast period of 2017–2024. The piezoresistive sensor market generated the highest revenue share in the global pressure sensor market. With the emergence of advance technologies for different gas sensing, the market is expected to be valued at \$1.4 billion by 2024 at a CAGR of 6.86% in the forecasting period of 2017–2024. The rising demands of oxygen gas in the healthcare sector such as in the anesthesia machines, ventilators, oxygen monitors, and in automotive and transportation application are driving the oxygen gas sensor market. The consumer electronics market is expected to grow at the highest rate as the gas sensors are believed to be integrated with smartphones and other wearable devices to detect alcohols, carbon dioxide, carbon monoxide, and nitrogen dioxide. The optical sensing market is estimated to grow from \$1.12 billion dollars in 2016 to \$3.46 billion by 2023 at a CAGR of 15.47% between 2017 and 2023. The demand for optical sensors is attributed to its accuracy and the ability to withstand harsh environments in aerospace, defense sectors, and oil and gas industries. The increasing investments in the R&D activities on optical sensors drive the growth of the market. The magnetic sensors market is expected to reach \$4.16 billion by 2022 at a CAGR of \$4.16 between 2016 and 2022.

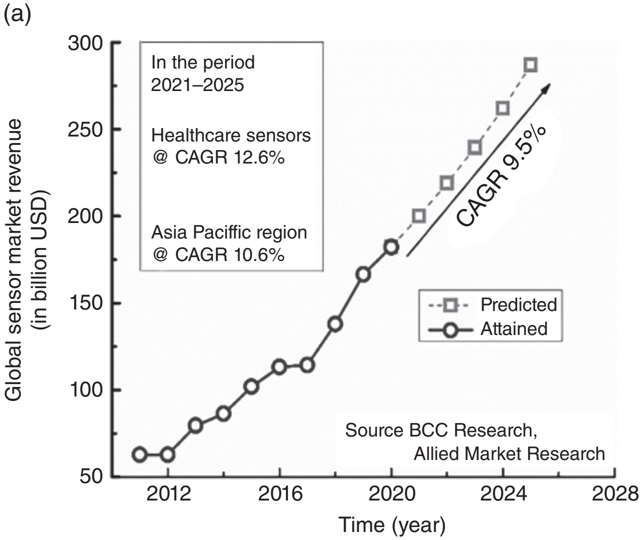


Figure 1.1 (a) Global sensor market revenue from 2010 to 2020 and predicted growth with CAGR of 9.5% for 2021–2025. (b) Global sensor market trends for different devices as predicted by IDTechEx. *Source:* (a) Adapted from BCC Research, Allied Market Research.

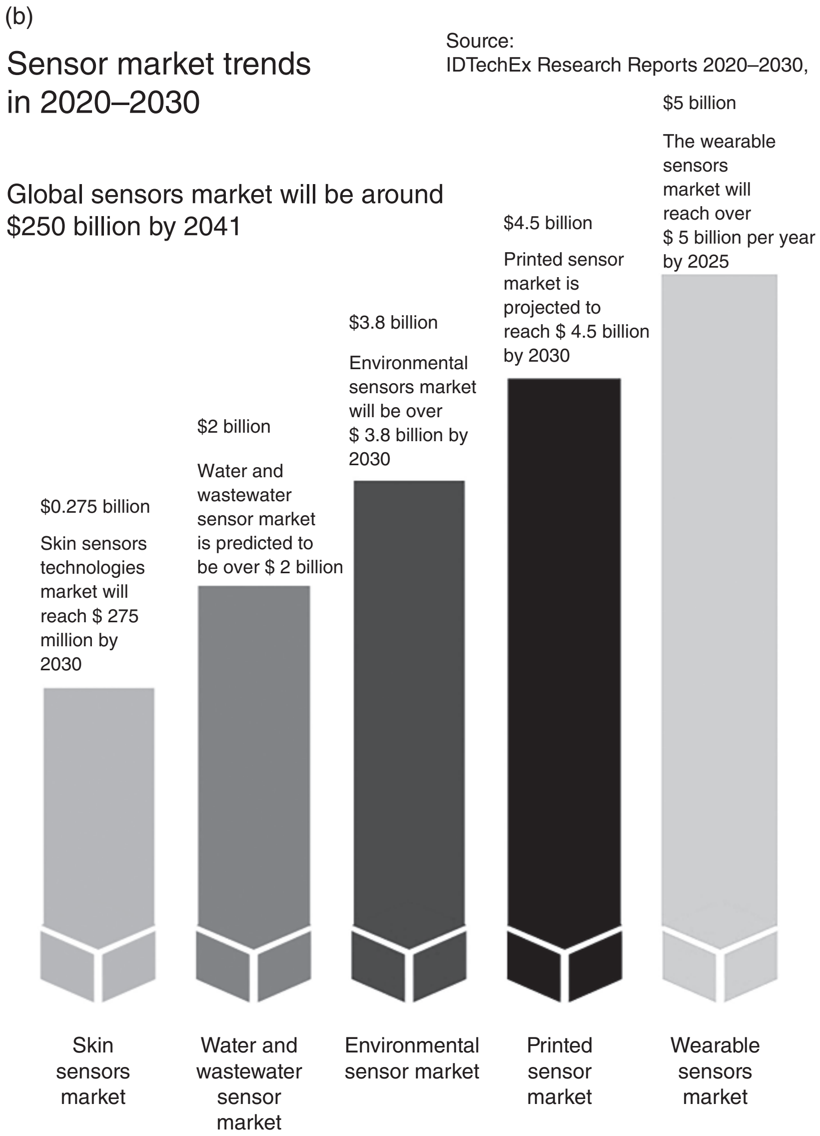


Figure 1.1 (Continued)

Table 1.1 Various sectors of solid-state sensor market and their respective predicted market revenue per year.

Materials/device/sensor market	Prediction until year	Predicted revenue per year (in billions)
Graphene market	2031	\$0.7
Fluoropolymer/electronics market	2041	\$14
Printed electronic materials market	2031	\$6.9
3D printing materials	2030	\$18.4
Wearable sensors market	2025	\$5
CNT market	2030	\$0.750
3D electronics	2030	\$3
Advanced photovoltaics market beyond silicon	2040	\$40
Sensors market	2041	\$250
Printed sensor market	2030	\$4.5
Skin sensors technologies	2030	\$0.275
Wearable technology	2019 attained	\$70
Environmental sensors market	2030	\$3.8
Flexible electronics in health care	2030	\$8.3
Flexible hybrid electronics	2030	\$3
Biosafe polymer market	2030	New market
Harvesting for roads and sensing for IoT and healthcare market for piezo transducers	2030	\$1
Piezoelectric-based sensing market in health care beyond imaging	2029	\$1.04
RFID sensor tags and systems	2028	\$0.904
Robotic sensing	2027	\$16.1
Water and wastewater networks sensor market	2030	\$2
Solid-state batteries	2030	\$6
Wearable technology for animals market	2030	\$22

1.1.2 Solid-State Sensors: A Recipe for Smart Sensing Systems

The rapid growth solid-state sensor market can be attributed to the development of computer-controlled processes and remote monitoring of industrial process in real time. With the advent of microfabrication and miniaturization of devices, system-on-chip (SOC) sensors have drawn significant attention from the researchers from academia and industries. Currently due to the growing demands of on-chip integrated devices, the class of solid-state sensors has surpassed the traditional sensing techniques such as the electrochemical and the chromatographic methods in terms of scopes, benefits, and reliability. The development of solid-state sensors not only promises integrated multiple sensors on a common chip, but also shows potential in closer interfacing with the computers for remote monitoring of various processes which aid computerized manufacturing and process control. There are many types of solid-state sensors, which are in everyday use or in the different stages of development. They encompass a wide realm of sensing technologies including the chemical sensors (gas and biosensors), physical sensors (e.g. strain, pressure, temperature), acoustic sensors (e.g. bulk and surface acoustic wave devices), optical sensors (optical waveguide, infrared detectors), thermochemistry (e.g. microcalorie and microenthalpy sensors), and magnetic sensors. The major advantages of the solid-state sensors lie in the simplicity, portability, microfabricability, and reliability. The simplicity in operation of the solid-state devices relates to the noninvolvement of complex equipment and skilled operators for sensing. The miniaturization compactness and feasibility for on-chip integration lends portability to solid-state sensors. The solid-state sensors are compliant to batch and planar fabrication techniques, which reduces the cost of fabrication. The solid-state sensors overcome the problems of inconsistent liquid-phase sensing processes, which make them reliable for long-term use.

1.2 Evolution of Solid-State Sensors

1.2.1 Origin and Early Developments in Detection Devices

The need for devices arises from its necessity in public welfare or from the demand in commercial market. Originated in necessity and demand, and conceptualized through suitable understanding, the evolution of sensors went through several scientific challenges and technological advancements, which sometimes spanned over many centuries. The ruler or the measuring rod can be considered as the first measuring tool which was reported to be used in the Indus Valley civilization in 2650 BCE [13]. However, an astronomical device and an inclinometer called the Astrolabe (Figure 1.2a), invented by Apollonius of Perga around 200 BCE, can be regarded as the first device to be invented in the history of mankind [14, 15]. The seismometer, invented by Zhang Heng of the Han dynasty in 132 CE [16], and the Mariner's compass, invented in Southern India in 400 CE [17], were a few of the early detection equipment that were developed in the Medieval era.

The evolution of transducer/sensor took place in diverse realms of fields, including those associated with health care originated in the same era but underwent

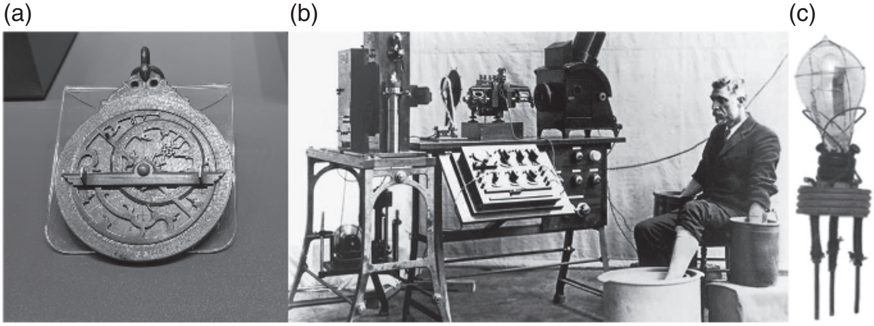


Figure 1.2 (a) The front face of the ancient Astrolabe. (b) Einthoven with his EKG machine. (c) The first vacuum tube invented in 1904 by John Ambrose Fleming. *Sources:* (a) Mustafa-trit20/Wikimedia Commons/CC BY-SA 4.0. (b) Informa UK Limited.

massive transformation through the modern era and continuing in the electronic era (post 1895). One such device which has been through the journey of evolution from its medieval form to its present form is the modern-day pulse meter. The modern-day pulse meter supported with wireless features and other physiological sensors and regulated through AI can be considered as a unique example of scientific, technological, and engineering device evolution. The authors have traced back the evolution of pulse meters since its inception when people relied on qualitative diagnosis to a more complex and detailed informative device in its present form. That pulse diagnosis directly related to human health was realized in 350 BCE by Chinese physician Bian Que (401–310 BCE). Later in 305 BCE, the Praxagoras of Cos (340–??[1] BCE) [18], the teacher of Herophilus of Chalcedon (335–280 BCE), became the first Greek physician to feel the pulse in order to observe the health of the ill. Having understood the importance of pulse diagnosis, the ancient researchers felt the need for a device that would help them to count the heart beat and investigate the pulse rate in unhealthy humans. In 290 BCE, Greek physician Herophilus of Chalcedon (335–280 BCE) devised a water clock to count the human pulse to analyze the rhythm and heartbeat, though it was not considered as a complete device [19]. Although the ancient inventions and breakthroughs are not well documented, but are reported in scriptures. A Polish Professor Joseph Struthius (1510–1568) was the first to present a graphic image of the pulse in 1555 and

---

[1] There are no historical details about his personal life. It is believed that he suffered the ravages of the terrible fire at the Library of Alexandria or, in a speculative sense, he might have been persecuted for his probable forbidden practices of dissections on human cadavers. Therefore, what little we know about him comes from his colleagues and pupils, such as Galen, Herophilus, or Erasistratus.

introduced the concept of a device that could mechanically register the pulse [20]. It was after the Italian physician, mathematician, and philosopher Galilei (1564–1642) in 1601 who correlated his own pulse with the pendulum movements of a clock, an Italian Professor of Medicine Santorio Santorio (1561–1636) in the year 1602 successfully counted the pulse using this pendulum [21]. This was the first pulse meter. Incidentally, Galilei and Santorio invented the thermoscope and the clinical thermometer in 1593 and 1625, respectively [22]. In 1707, an English physician Sir John Floyer (1649–1734) invented the "one minute pulse watch" for a correct pulse measurement. Floyer was one of the first to measure the pulse in daily practice and used the device to obtain accurate pulse rate measurements [23]. The devices invented in the modern era were mostly mechanical devices with moving parts and was only considered as mechanical devices.

A more advanced electronic record of heartbeat was obtained in 1872 by Alexander Muirhead when he attached wires on the wrist of the patient. Augustus Waller invented an ECG machine in 1887, however the more practical and sensitive one was invented by Einthoven in 1901 [24] (Figure 1.2b). In 1924, Einthoven was awarded the Nobel Prize in Medicine for his pioneering work in developing the ECG. The electronic era commenced with the discovery of wireless transmission in 1895 by Russian scientists [25, 26] and riding on the advancements in electronics and miniaturization, wireless ECG-based heart rate monitor was invented in 1977 by Polar Electro as a training tool for the Finnish National Cross Country Ski Team [27]. In 2005, Textronics, Inc., introduced the first garment with integrated heart sensors in the form of a sports bra [28]. Special materials in the sports bra sense heart rate from the body and transmit it to a wrist receiver. Recently in 2020, researchers have developed smart healthcare system in IoT environment that can monitor a patient's basic health signs in real-time using integrated heart beat sensor, body temperature sensor, room temperature sensor, CO sensor, and CO_2 sensor in a sensor system [29].

Earlier the invention of thermionic emission in 1873 marked the beginning of a new era which revolutionized the scope of detection devices. Thomas Edison's discovery of electric current in 1883 was a huge leap in mankind and laid the foundation to the present-day electronics (Figure 1.3). Following the discovery of unilateral conduction across the junction of a semiconductor (Galena crystal) and a metal by KF Braun in 1974, JC Bose was the first to use this crystal semiconductor for detecting radiowaves in 1894 [30]. This concept of rectifying contact between metal semiconductor junctions was used by Braun and GW Pickard to develop radiowave detector (commonly called Cat whisker detector) in which they replaced Galena crystal with silicon [31]. The Cat whisker detector was the first solid-state electronic detection equipment that was patented in 1906. In 1916 and 1917, Paul Langevin and Chilowsky developed the first ultrasonic submarine detector using an electrostatic method (singing condenser) [32]. The amount of

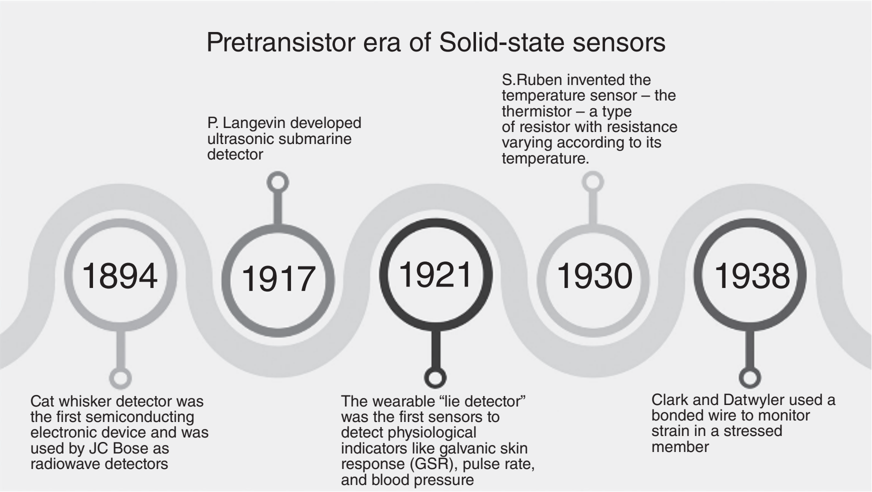
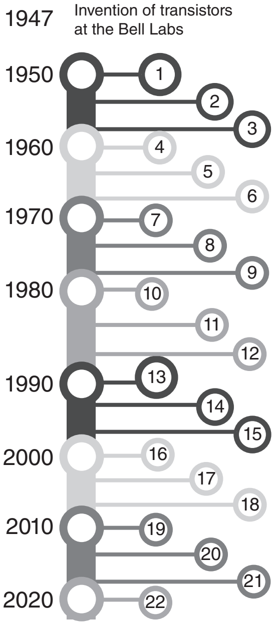


Figure 1.3 Timeline of key inventions of solid-state devices in the electronic era.

time taken by the signal to travel to the enemy submarine and echo back to the ship on which the device was mounted was used to calculate the distance under water. The first wearable solid-state detection equipment was the polygraph which was invented in 1921 by a medical student named John Augustus Larson and worked on the Galvanic response of the skin [33]. Subsequent inventions during the modern age continued in different field of research until the invention of the transistor in 1947 which boosted the field of solid-state electronics and sensing systems.

1.2.2 Solid-State Electronics: Post Transistor Era

Vacuum tubes, invented in 1904 by John Ambrose Fleming (Figure 1.2c), formed the basic electronic components for use in television, radar, telephone, and industrial process control applications [34]. The scientific community turned toward solid-state electronic materials as alternative solutions to overcome the challenges of vacuum tube-based devices that were widely used as amplifiers and rectifiers prior to 1940s. The invention of semiconductor devices in the late 1950s led to the development of solid-state devices which are smaller, efficient, reliable, and cost-effective than the vacuum tube-based devices (Figure 1.4). Furthermore, the solid-state devices were associated with low heat dissipation and fast response. The solid-state devices work on the principle of electronic conduction in the material in contrary to the vacuum tube devices which operate through thermionic



1 1957: Mason and Thurston first reported silicon strain gauges for measuring displacement, force, and torque

2 1958: Kulite Semiconductor first patented Si-based strain sensor

3 1958: Miniaturized devices on IC boards were manufactured by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor

4 1965: Statham introduced the first thin-film based pressure transducers for high pressure measurement

5 1967: MOSFET used as product detector by WM Stobbe

6 1967: MOSFET used as product detector by WM Stobbe

7 1970: Invention of first BioFET in the form of ISFET

8 1971: Hurst patented the first touch sensor called Elograph

9 1972: Yellow Springs Instruments launches first comercial glucose biosensor

10 1979: Bob Bell developed ceramic-based capacitive pressure transducer for low pressure range

11 1984 The first amperometric biosensor for glucose using ferrocene and glucose oxidase

12 1985: The term “chemiresistor” was coined by Wohltjen and Snow

13 1990: S Terry et al developed a Silicon pressure transducer arrays for blood pressure measurement

14 1993: The first webcam is invented at the Cambridge University

15 1997: R. Picard designed and developed “Smart Clothes” that monitored continuous physiological data from the wearer

16 2003 Vilatron C series was the worlds first fully digitized pacemaker

17 2003: Nanotubes covered with enzymes was used as single-molecule biosensors to detect pH changes. This discovery opens the field of nanobiosensors

18 2003, Garmin released the Forerunner, a bulky smartwatch that measured, speed, distance, pace, and calories burned

19 2014: A graphene biosensor can detect cancer biomarkers

20 2012: New noninvasive biosensor can detect blood, glucose in saliva, tears, and urine.

21 2012: Proteus Digital Health lauches ingestible health feedback system and approved by FDA

22 2020: Worlds first ultrasound biosensor to monitor drug level in blood

Figure 1.4 Timeline of key contributions in solid-state sensors.

emission. With the advent of microfabrication techniques of devices, the demand for solid-state (semiconductor) devices increased manifold due to their batch fabricability which cuts down processing cost. Thus, the rise of semiconducting materials and solid-state devices provided a new dimension to the field of electronics and associated devices. The invention of transistors by American Physicists John Bardeen, Walter Brattain, and William Shockley in 1947 at the Bell Labs virtually redefined the modern-day electronics [35, 36]. This transistor (Figure 1.5a) was based on point contact configuration and paved the way for cheaper radios, televisions, calculators, computers, and other devices. Bardeen, Walter, and Shockley (Figure 1.5b) were awarded with the Nobel Prize in Physics in the year 1956 for their study on semiconductors and the discovery of the transistor effect, and later in the year 2009 this feat was acknowledged on the list of IEEE milestones in electronics. Shockley continued his studies on semiconductor and along with Gordon Teal and Morgan Sparks successfully demonstrated the working of N-P-N bipolar transistor in the year 1950 (Figure 1.5c). The striking advantage of transistors lies in the potential use as amplifiers and switches. Due to the small size and energy efficiency of the transistors, it was widely used in the design of complex electronic circuits with high switching speeds and energy efficiency.

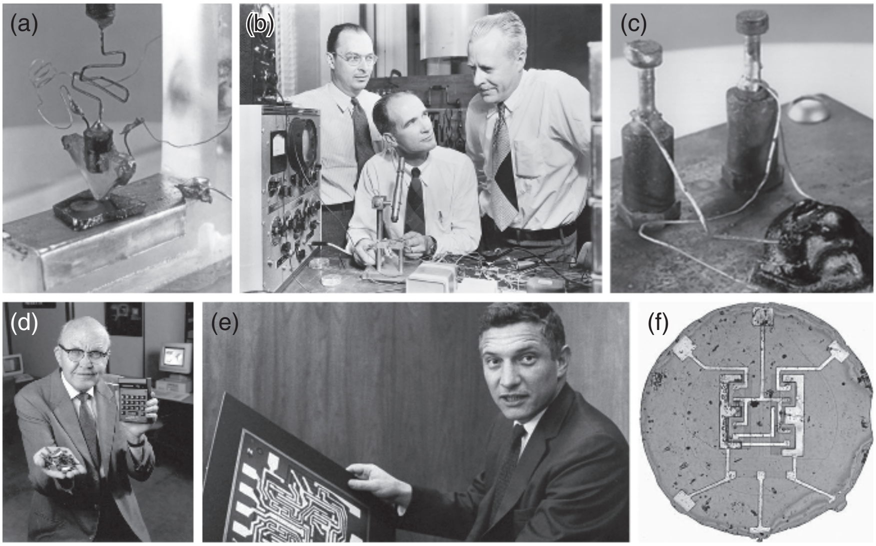


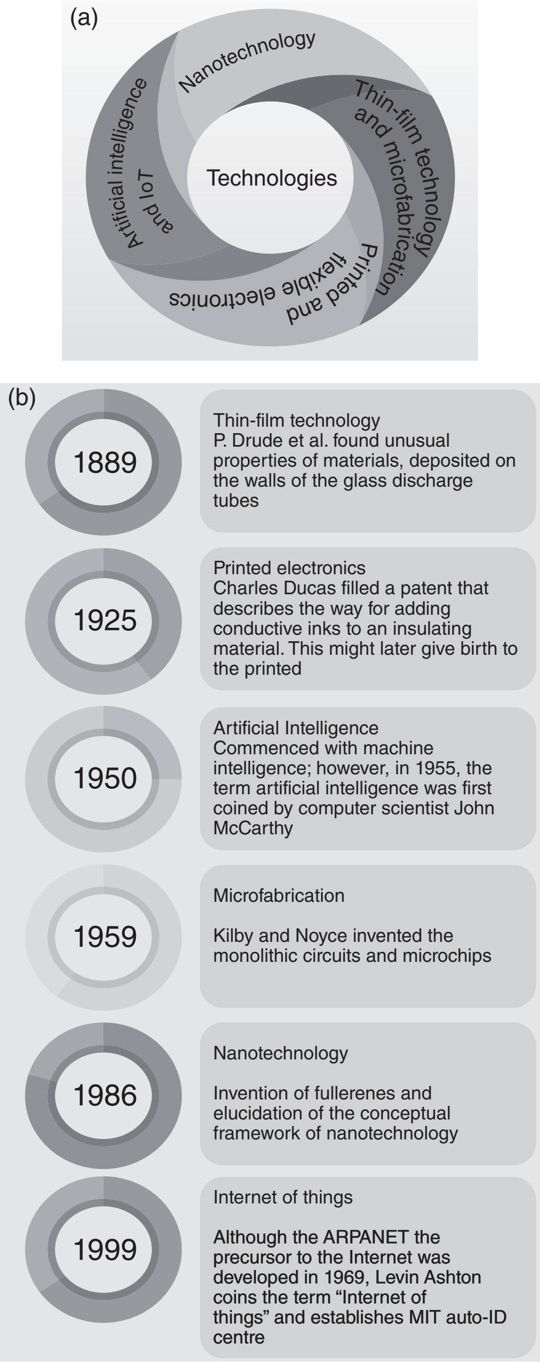
Figure 1.5 The foundation and pillars of modern-day solid-state electronics. (a) The first transistor of the world, born in Bell Labs in 1947, invented by (b) the American Physicists John Bardeen (L), Walter Brattain, and William Shockley (R). (c) Sparks N-P-N bipolar transistor of 1950. (d) Jack Kilby with his invented first pocket calculator. (e) Robert Noyce with his invented monolithic IC-based motherboard. (f) The first monolithic (2D) integrated circuit developed at Fairchild Semiconductor in 1959 by R. Noyce. Kilby and Noyce are recognized as the inventors of the microchip. Kilby received the Nobel Prize in year 2000 for his contribution to integrated circuit. *Sources:* (b) AT&T/Wikipedia Commons/public domain. (d) The Library of Congress. (e) Intel Free Press/Wikipedia Commons/CC BY-SA 2.0. (f) Fairchild/Courtesy of the Computer History Museum.

The need for the miniaturization of electrical components arose when they were required to be assembled on a single chip. Miniaturization further enhances the energy efficiency of the circuit and reduces the time lag in response. Miniaturized devices on IC boards were manufactured by Jack Kilby at Texas Instruments, and Robert Noyce at Fairchild Semiconductor in 1958 and 1959, respectively. Researchers were successful in fabricating not only transistors but also resistors, capacitors, and diodes on a single monolithic layout to form an electronic chip. Kilby used germanium and Noyce used silicon for the semiconductor material. In 1959, both parties applied for patents. Jack Kilby (Figure 1.5d) and Texas Instruments received US patent #3,138,743 for miniaturized electronic circuits [37]. Robert Noyce (Figure 1.5e) and the Fairchild Semiconductor Corporation received US patent #2,981,877 for a silicon-based integrated circuit [38]. In 1961, the first commercially available integrated circuits (Figure 1.5f) came from the Fairchild Semiconductor Corporation. All computers then started to be made using chips instead of the individual transistors and their accompanying parts. Jack Kilby holds patents on over 60 inventions and is also well-known as the inventor of the portable calculator (1967) [39, 40] (Figure 1.5d).

With the advent of miniaturization and advanced microfabrication technique, researchers designed new devices aimed at different applications. As evident from published literature, the researchers have extensively worked on different devices and sensors and classified them in accordance with the transduction principle used in the device. Although the terms "sensor" and "transducer" are often used as synonyms, the American National Standards Institute (ANSI) standard in 1975 preferred the latter over the former [41]. However, the scientific community has adopted the term "sensor" to define *a device which provides a usable output in response to a specific measurand* and thus is commonly used in scientific articles. The output of a sensor may be any form of energy. Many early sensors converted (by transduction) a physical measurand to mechanical energy; for example, pneumatic energy was used for fluid controls and mechanical energy for kinematic control. However, the introduction of solid-state electronics created new avenues for the development of sensor systems aided by computer-based controls, archiving/recording, and visual display. The modern-day sensor system is often associated with algorithms, AI, and other techniques which require electrical interfacing with microchips and computer-aided controls, thereby broadening the definition of a sensor to include the systems interface and signal conditioning features that form an integral part of the sensing system. With progress in optical computing and information processing, a new class of sensors, which involve the transduction of energy into an optical form, is likely. Thus, the definition of a "sensor" is likely to continue evolving with time.

1.2.3 Emergence of New Technologies

The evolution of solid-state electronics and its contribution in the field of solid-state sensors is largely attributed to the emergence of new technologies which facilitated the transformation of different aspects of solid-state sensors since its origin. Emergence of new technologies and their advancements over the years (Figure 1.6) have led to technological convergence of their key features toward the evolution and transformation of solid-state electronics that have forced scientists to setup new benchmarks in defining solid-state sensors. This technological convergence has shifted the paradigm of research in solid-state sensors from semiconductor electronics to a more open-ended approach. In this section, we will discuss about the key technologies that helped transform solid-state research. The key new technologies with their evolutionary timeline are represented in Figure 1.6.



Thin-film technology
P. Drude et al. found unusual properties of materials, deposited on the walls of the glass discharge tubes

Printed electronics
Charles Ducas filled a patent that describes the way for adding conductive inks to an insulating material. This might later give birth to the printed

Artificial Intelligence
Commenced with machine intelligence; however, in 1955, the term artificial intelligence was first coined by computer scientist John McCarthy

Microfabrication

Kilby and Noyce invented the monolithic circuits and microchips

Nanotechnology

Invention of fullerenes and elucidation of the conceptual framework of nanotechnology

Internet of things

Although the ARPANET the precursor to the Internet was developed in 1969, Levin Ashton coins the term “Internet of things” and establishes MIT auto-ID centre

Figure 1.6 (a) Emerging technologies and their (b) timeline of events, which lead to the evolution of solid-state sensors.

1.2.3.1 Thin-Film Technology

The thin-film technology evolved at the end of the nineteenth century when Drude et al. [42] in 1889 found unusual properties of materials deposited on the walls of the glass discharge tubes, which were different from their bulk counterpart. Over the years, thin films of different materials deposited by wide range of techniques including physical (1940s) and chemical (1970s), vapor deposition, atomic layer deposition, molecular beam epitaxy (1980s), spin coating, dip coating, sol gel, and Langmuir Blodgett method have been well characterized and understood by electron diffraction method (1927), electron microscopy (1940), surface analytical methods (1960s), atomic resolution surface imaging techniques like STM and AFM (1980), and ultrahigh-resolution TEM (1990). The advent of more advanced thin-film deposition and characterization techniques such as UHV TEM, fast STM, and synchrotron in early twenty-first century has boosted the solid-state sensor industry due to the thickness controllability, thus providing tunability in sensor performance. Thin films have taken a dominant role in revolutionizing the development of new active and passive sensor elements which have led to a drastic metamorphosis of the electronic devices especially the solid-state sensors. The physical and chemical properties of the thin film largely depend on the material, microscopic structure, and the parameters (e.g. temperature and pressure) utilized to generate the desired microstructure. The microstructure in the thin-film technology relates to the phase state, morphology of the grains and surfaces, orientations of the crystals planes, texture, chemical composition, homogeneity, and the substrate and thin-film interface. The key feature of the thin-film technology lies in the evolution of self-organized structure by atom by atom adding process at temperatures far from dynamic equilibrium which allows controlled synthesis of metastable phases and artificial structures and multilayers [43]. This self-organization in thin film is a thermal activated process and initiates with nucleation through migration of atoms, followed by crystal growth by surface diffusion, and grain growth and restructuring by bulk diffusion [44]. However, contaminations can produce adverse effect on the desired structure and property. The evolution of the thin-film technology is truly the backbone for the growth and widespread acceptance of modern-day solid-state sensors.

1.2.3.2 Advancements in Micro- and Nanofabrication

The inventions of the transistors and integrated circuit in the 1940s and 1950s, respectively, gave rise to a miniaturization trend in electronics. Miniaturization through microfabrication and micromachining has revolutionized the world of solid-state sensors. These microfabrication processes have evolved and been modified into advanced technologies that are pushing the boundaries of resolution, feature sizes, and aspect ratios. The term microfabrication was coined by the semiconductor industry. Microfabrication is a multiple step sequence of photolithographic and chemical processing which are used to make microscopic devices and electronic circuits on silicon, polymer, and other biomaterials substrates (rigid or flexible).

With the improvement in microfabrication techniques, smaller and more complex integrated circuits were built, which facilitated the dense packing of electronic components on a given area of the microchip. Due to the extremely small dimension of the structures certain high-tech tools must be used when performing microfabrication work. The major concepts and principles of microfabrication are photolithography, doping, deposition, etching, bonding, and polishing. A typical microdevice is fabricated by a sequence of microfabrication steps including micromachining, deposition, followed by patterning the film with various microfeatures using photolithography and subsequently etching parts of the undesired area. These processes are detailed in Chapter 2. Industrial microfabrication process is a cumbersome sequence of events where a typical memory chip requires approximately 30 lithography, 10 oxidation, 20 etching, and 10 doping steps to fabricate. Microfabrication is used in the development of integrated circuits on a chip, most of the miniaturized sensors including the semiconductors, microfluidic devices, solid-state sensors, MEMS, and BioMEMS.

Thin film plays a key role in microfabrication where microchips are typically created using multiple thin films. For electronic devices, the patterned films contain conductive metals that allow for the flow of electricity, while for optical devices, thin films are in the form of reflective or transparent films to improve visibility and clarity. The thin film may also be chemical and biological materials in the form of active sensing or encapsulation material often found in medical devices and gas sensors. Dielectric thin films of polymers are used in capacitive sensors and gate dielectric as the insulation material.

The process of microfabrication is not only limited to the deposition patterning and etching of polymers and semiconducting materials, but also offers a way to produce homogeneous monodisperse particles that are not only spherical, but having controlled or asymmetrical shapes and architectures with a specific size to be fabricated, which is not possible with other methods [45, 46]. Using microfabrication techniques such as particle replication in nonwetting templates [47], microcontact hot printing [48], step and flash imprint lithography [49], and hydrogel template [50] achieve such feat. Microfabrication techniques are used to generate patterns of cells on surfaces. This cellular patterning is a necessary component for cell-based biosensors, cell culture analogs, tissue engineering, and fundamental studies of cell biology [51]. Moreover, alternative techniques, such as microcontact printing [52, 53], microfluidic patterning using microchannels [54, 55], and laminar flow patterning [56], have been developed for use in biological applications. Microfabrication is even used in advanced manufacturing processes for engineered neural prosthetics where high-resolution neuroelectrodes are fabricated with the aim of reducing the size of the electronic component. This is achieved by 2D printing of neural arrays or fabricating topographical and biochemical features on the surface of engineered neuroelectrode [57].

1.2.3.3 Emergence of Nanotechnology

The emergence and subsequent evolution of nanomaterials have revolutionized research in the field of materials science. The convergence of nanomaterial and several microfabrication techniques have led to diverse sensors with different applications [58–63]. The reduction of particle size and tuning the particle morphology of nanomaterials from micro to nano size has led to unique properties with versatile applications. The reason for the nanomaterials to exhibit unique/enhanced properties is due to the large surface-to-volume ratio and quantum confinement effect. The word nanoscience refers to the study, manipulation, and engineering of matter, particles, and structures on the nanometer scale (one millionth of a millimeter). Due to the quantum mechanical effects, the properties of materials in nanoscale differ from the properties of the same material in bulk form. Material properties, such as electrical, optical, thermal, and mechanical properties, are governed by the morphology and particle size of the nanomaterial, where properties of materials larger than 100 nm tend to show bulk properties. Nanotechnology is the application of nanoscience leading to the use of new nanomaterials in sensors and devices. Due to tunable properties of nanomaterials, nanotechnology has the capability and promise to provide us with custom-made materials and products with new enhanced properties, new nanoelectronics components, new types of "smart" medicines and sensors, and even interfaces between electronics and biological systems.

Although the field of nanoscience and nanotechnology is relatively new and scientific developments in these fields bloomed after 1990, the key concepts of these branches of science were practiced over a longer period of time where the earliest evidence dates back to 600 BCE. Pottery shards excavated from Keeladi in India's southern state Tamil Nadu and reported in the year 2020 showed unique black coating on the inner surface of the pottery, which was investigated by the Indian researchers at the Vellore Institute of Technology, India, found to be carbon nanotubes [64] (Figure 1.7a). The use of metal nanoparticles in the fourth century Roman era was evidenced in the Lycurgus Cup which is kept in the British Museum. The glass contains gold–silver nanoparticles which are distributed in such a way that it appears green in daylight, but changes to red, when illuminated from the inside. The Damascus steel sword from the Mesopotamian civilization made between 300 and 1700 CE contained nanoscale wires and tube-like structures which exceptionally enhanced the sharp cutting edge of the sword. However, the re-emergence of nanotechnology in the 1980s was attributed jointly to the invention of advanced experimental tools such as scanning tunneling microscope,

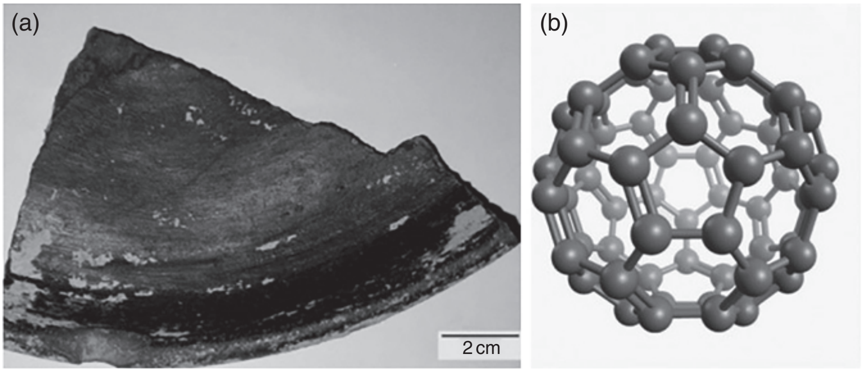


Figure 1.7 (a) Artifacts of pottery shards dated to 600 BCE unearthed from an archaeological site in Keeladi, Tamil Nadu showed evidences of carbon nanotubes. (b) Molecular structure of Fullerene, an allotrope of carbon discovered in 1986. *Sources:* (a) Springer Nature Limited. (b) The Trustees of the British Museum.

invention of fullerenes (Figure 1.7b), and elucidation of the conceptual framework of nanotechnology in 1986 [65]. The growing awareness on nanotechnology led to the discovery of carbon nanotubes in 1991 [66], which triggered multiple avenues of research and led to understanding of peculiar material properties in nanoscale, opening up applications in diverse fields.

Systematic research developments on the experimental as well as the conceptual aspects of nanoscience and nanotechnology resulted in vivid understanding of the quantum size effects and its role on material properties. The findings opened up new and exciting possibilities to tailor the chemical and physical properties of a material through exploiting and varying their nanoscopic properties. Unusual properties of nanomaterials led to the evolution of new devices which are aimed at smart sensor application. Controlled particle size and consistent yield of nanostructured material facilitated the widening of the realm of nanotechnology and encouraged researchers to integrate nanomaterials into smart devices and produce advanced and cost-effective sensor systems.

1.2.3.4 Printed Electronics on Flexible Substrates

Research on printed and flexible electronics is constantly evolving with extensive scope for innovation and has led to new avenues for the development of new age sensors. Printed electronics is an all-encompassing term for the printing method used to create electronic devices by printing on a variety of substrates. Printed circuitry is widely used in organic or plastic electronics, where carbon-based and carbon–metal composite inks are extensively utilized. The advent of flexible keyboards, antennas, and electronic skin patches has boosted the demand for printed electronics. Printed electronics is one of the fastest growing technologies today and the importance is already realized in several industries including health care, aerospace, and media.

The evolution of printed electronics initiated in 1903 when famous German Inventor Albert Hanson filed a British patent for a device described as a flat, foil conductor on an insulating board having multiple layers. He called the conductor as “Printed Wires,” and showed that we can punch a hole into the two layers and had perpendicular wires to establish electrical connectivity. In 1925, Charles Ducas filed a patent that describes the way for adding conductive inks to an insulating material (Figure 1.8a). This later gave birth to the printed wiring board

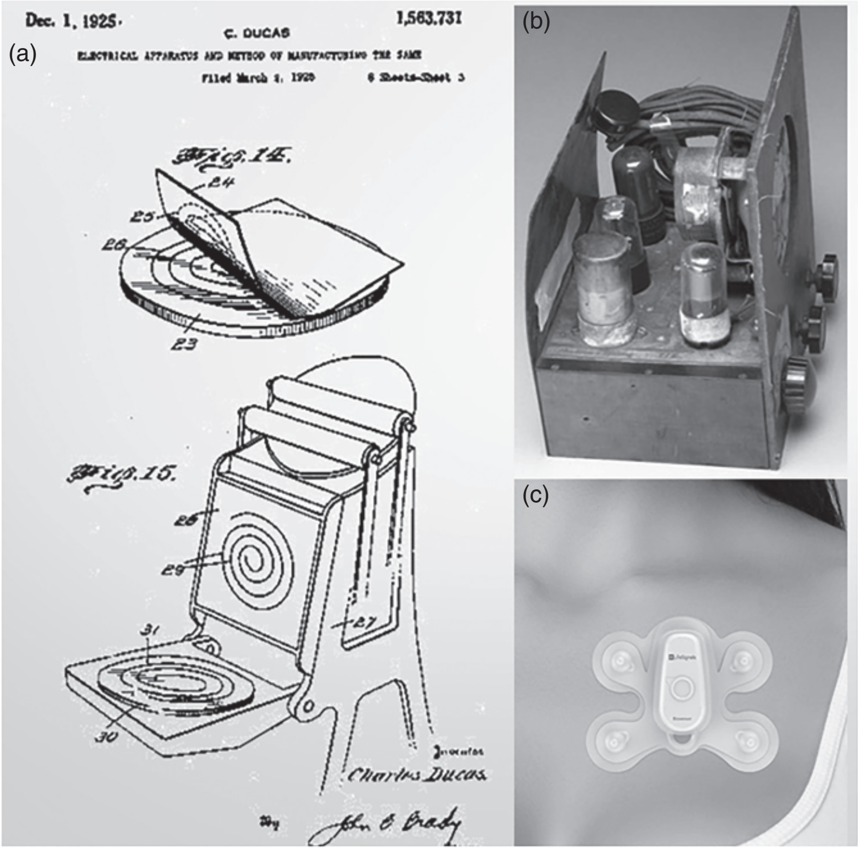


Figure 1.8 (a) Charles Ducas patent drawing. (b) A radio made by Paul Eisler that uses first printed circuit board (PCB). (c) The Life Signals Biosensor Patch 1AX enable remote wireless mass population monitoring for COVID-19. *Sources:* (b) By Georgi Dalakov - http://history-computer.com/ModernComputer/Basis/printed_board.html, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=19448601. (c) Courtesy of how2electronics.com.

(PWB). This was used as a flat heating coil and showed the way for printed circuitry. The period from 1930 to 1945 is marked as the most significant time in the history of printed circuit board (PCB). The PCB was used in proximity fuse invented by the British for high-velocity artillery shells, which needed to fireside precisely over massive distances in either sky or land. In 1936, Paul Eisler, an Austrian living within the United Kingdom, filed a patent for copper foil circuit on a nonconductive base of a glass terming it as printed circuit [67–69]. Eisler later took this concept one step further for large-scale production of radios (Figure 1.8b) by the United States during World War II in 1943, which might pave the way for future military applications. Printed circuit technology was released for commercial use in the United States in 1948 (Printed Circuits Handbook, 1995). Widespread production of printed electronics for household use began in the 1960s when the PCB became the foundation for all consumer electronics. Over a half-century since its inception, printed electronics have evolved from PCBs to today's use of solution-based conductive inks on flexible substrates for the development of RFID, photovoltaic, and electroluminescent technologies. At present, printed electronics have revolutionized the solar cell industry and wearable sensors market. In 2011, researchers from MIT created a flexible solar cell by inkjet printing on normal paper [70]. In 2018, researchers at Rice University have developed organic solar cells which can be painted or printed onto surfaces [71]. In 2020, researchers have successfully placed wearable circuits directly onto the surface of human skin to monitor health indicators, such as temperature, blood oxygen, heart rate, and blood pressure. This printed wearable electronics for health monitoring combines soft on-body sensors with flexible PCBs (FPCBs) for signal readout and wireless transmission to healthcare workers [72]. In 2020, following COVID-19 pandemic, some companies have developed electronic skin patches for monitoring a patient's temperature remotely, the benefit being that the patient does not need to come into contact with healthcare professionals to take their temperature which may expose them to the virus (Figure 1.8c). Again conductive ink has been used in sensor test systems as part of a system to detect infections, including COVID-19 [73, 74]. Furthermore, Cu nanoparticles due to their antiviral benefits were 3D printed onto surfaces such as door handles to combat spread of infection [75]. Printed force sensors have been applied into mats to alert shoppers where they are standing too close to each other.

Owing to the advantages of printed electronics, the sensors and devices have become light weight, flexible, and cost-effective, making them more appealing to a wide cross-section of industries. Printed circuits have the potential to reduce costs and technical constraints typically associated with mass producing electronics. In addition, printed electronics have paved the way for flexible sensors and allied wearable devices which have opened up new set of applications. Printed electronics holds promise to change the photovoltaic industries due to less expensive polymer electronics.

The benefits of printed electronics are listed as:

1) Use of custom-made organic printable inks
2) Use of various different substrates including bendable and biodegradable
3) Cost-effective and fast fabrication
4) Attractive and flexible form factor
5) Ease of production
6) Ease of integration

Although printed electronics have been around since 1960s, a major burst in total revenue was seen in the hybrid age after year 2000. According to IDTechEx publication, the total printed electronic revenue in 2011 was reported to be at $12.385 (billion) and expected to reach $330 (billion) in 2027. This huge increase in revenue is attributed to the incorporation of printed electronic into cell phones. Despite the fast growing market of printed and flexible electronics, researchers are still working on the development of best performance conductive inks for on-fabric use and its use on different substrates. Printed electronics continue to face challenges in batch fabrication as the processes are so new that trial and error and testing are critical to success.

1.2.3.5 Smart Devices with Artificial Intelligence

Smart sensors are expected to perform intelligently like humans and possess multifunctional and flexible sensing systems involving vision, handwriting recognition, speech recognition, human–robots interactions, gaming control, touch, smell, gesture control, and taste. These sensor systems can be made to operate more effectively and make smart decisions using AI. AI is a way of providing human-like intelligence and decision-making ability to machines, sensor systems, computer-controlled robots, and software with an aim to create expert systems and to implement human intelligence in machines. AI emerged in the mid-1950s, and evolved as a powerful tool for the development of smart sensor systems for automatically solving problems that would normally require human intelligence. The AI tools which are frequently used in sensor system are knowledge-based systems, fuzzy logic, automatic knowledge acquisition, neural networks, genetic algorithms, case-based reasoning, and ambient intelligence. These tools have minimal computation complexity and can be implemented with small sensor systems, single sensors, or system arrays with low-capability microcontrollers. Effective use of AI tools will contribute to the development of more competitive sensor systems and applications. Other technological developments in AI that will impact sensor systems include data mining techniques, multiagent systems, and distributed self-organizing systems. Ambient sensing involves integrating many microelectronic processors and sensors into everyday objects to make them "smart." This method is called sensor fusion. AI is useful when smart sensors are expected to perform advanced and complex task other than just reading raw data from the sensors.

Using AI, sensor fusion can be done easier and more accurately than with classical algorithms. Neural networks can cope with unknown situations much better. A combination of sensor systems and AI algorithms can empower intelligent robots with advanced capabilities in many areas such as environmental monitoring, gas leakage detection, food and beverage production and storage, and especially disease diagnosis through detection of different types and concentrations of target gases with the advantages of portability, low-power consumption, and ease of operation. Sensors equipped with AI in wearable and flexible smart electronics will meet the rising demand and growth in smart watch and sport bracelets in the market. Such devices as a part of IoT or as a part of our daily life can greatly enhance life quality of people and promote performance and interactivity of infrastructure in modern life. Contributions from various disciplines of research will help in the growth of smart AI-aided sensor systems.

1.2.3.6 IoT-Enabled Sensors

The internet of things, or IoT, is a system of interrelated devices, mechanical and digital machines, sensors or people (Figure 1.9a) that are provided with unique identifiers (UID) and transfers data over a network in the absence of any human-to-human or human-to-system interaction. The word "thing" in IoT refers to devices and sensors like wearable medical devices, an antenna connected to implantable device, built in sensors in tire of automobiles, RFID tags, or any device that has been assigned an IP protocol address and is able to transfer data over a network. IoT-enabled sensors share the sensor data they collect by connecting to an IoT gateway or other devices where data are processed in the cloud or analyzed locally. Such devices communicate with other connected devices in the network and also can act on the information received from another. The IoT enabled device/sensor at the receiving end collects the raw data and performs preprocessing in order to present relevant results. In advanced sensor systems, the raw data received from IoT-enabled device needs to be processed using AI for smart and intelligent decision making which can act as an alert for the users. In near future, the processing of the data from multiple sensors that are remotely connected to each other is believed to take place in cloud where the role of IoT-enabled devices will be effective. This will allow more complex sensor solutions through sensor data fusion for more advanced systems. The schematic working of IoT devices is shown in Figure 1.9b. The IoT-enabled devices together with AI can revolutionize the field of sensor systems, remote diagnosis, alerts for thefts, climate variations, natural disasters, medical emergency, and fire and thereby combat with appropriate measures without human interferences, thus making life more dynamic and smoother. The IoT helps people live and work smarter, as well as gain complete control over their lives. In addition to offering smart devices to automate homes, IoT is essential to business. IoT provides businesses with a real-time look

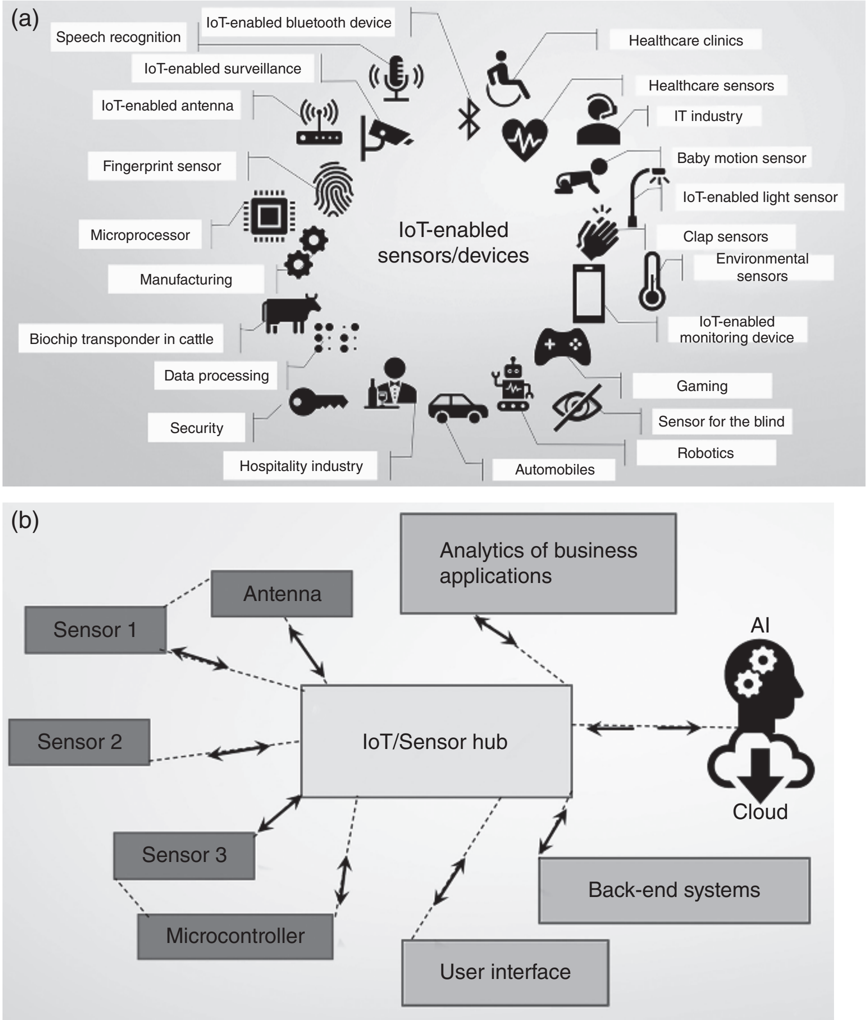


Figure 1.9 (a) Different IoT-enabled devices and systems. (b) Schematic representation of working of AI-supported IoT-enabled smart sensor system.

into how their systems really work, delivering insights into everything from the performance of machines to supply chain and logistics operations.

1.2.4 Paradigm Shift in Solid-State Sensor Research

With the advent of new technologies discussed in detail in Section 1.2.3, a distinct shift in paradigm is noticed in solid-state sensor research especially after the year 2000. The solid-state sensor research in the present day focuses on the development of devices which mostly uses nanomaterials, biomolecules, and organic polymers, are mechanically bendable, fabricated using solution process routes and thin-film technology, and cost-effective, makes them commercially attractive and integrable with microchips for the realization of smart sensing system with AI and IoT support. Some of the research products emerging out from the new technologies are listed below but are not limited to the following.

1.2.4.1 Organic Devices

Organic electronics is a newly emerging branch of modern electronics which deal with carbon-based materials often in the form of polymers and small molecules and molecules of living beings. Organic materials are known to be excellent insulators and used in wide range of applications until Heeger, MacDiarmid, and Shirakawa in the 1970s discovered that polymer polyacetylene when doped iodine can be made conductive with electrical conductivity enhanced many folds. Semiconducting behavior of organic polymer materials was first demonstrated by Tsumura et al. [76] in 1986 when they used polythiopene as semiconducting material in the channel of the first solid-state field effect transistor. The discovery of electrically conductive and semiconducting polymers drastically changed our perspective on polymer materials and formed the foundation of organic electronics. Over the years, the organic electronics have found their way from research laboratories to industrial applications and is due to replace Si electronics in commercial market in near future. The organic electronic market includes applications in the fields of light-emitting diodes (LEDs) [77], FET [78], and solar cells [79] and also open new avenues for other technologies.

Organic semiconductors based on polymers or small molecules consist of π-conjugated bonds with delocalized electrons which affect the electrical properties of the material [80, 81]. The molecules are held together by π–π noncovalent stacking interactions, which are weak Van der Waals, and dipole–dipole forces, which despite being feeble in nature, are sufficiently strong when large amount of interactions are involved [82]. The delocalized electrons in the π orbitals of the molecules constitute the π way through which the transport of electrons takes place under the influence of potential bias [83]. The amount of π-conjugated bonds and hence the number of delocalized electrons can be regulated by modifying the molecular structure using chemical methods. Thus, material property of organic conjugated polymers can be modified by substituting aliphatic side chains to aromatic part which may lead to a formation of distinct superstructure driven by the local phase separation between the flexible aliphatic part and rigid aromatic fraction or changes the molecular packing of the conjugated polymer. This affects the availability of delocalized electrons in the π way and thus on the transport of charge carriers from one molecule to another. An increased π-stacking distance reduces the hopping rate of charge carriers.

The principle advantage of using the conjugated polymers lies in the solution-based processability to fabricate devices, thereby allowing large area low-cost fabrication [84, 85]. Moreover, organic polymer materials are mechanically flexible and thus suitable for application in bendable devices [86]. The mass fabrication of the devices occurs by high-speed and inexpensive methods at low temperatures including printable circuits using inkjet and screen-printing techniques. Due to the low cost processing, the electronic elements can be used in the realization of radiofrequency identification (RFID) tags and sensors in which FETs play a key role [87]. Due to the low-cost fabrication process with conjugated polymers and their mechanical bendability [88] and strength, the organic materials [4, 89] and biopolymers [1, 90] finds their way into medical and healthcare applications.

1.2.4.2 Wearable Devices

The prehistory of wearable technology starts with the watch, which was worn by people to tell time. In 1500, the German inventor Peter Henlein created small watches that were worn as necklaces. A century later, men began to carry their watches in their pockets as the waistcoat became a fashionable item, which led to the creation of pocket watches. Wristwatches were also created in the late 1600s, but were worn mostly by women as bracelets. Today at the advent of modern-day technology supported by advanced microfabrication tools and techniques, wearable devices have encroached into our daily lives in the form of smart watches, medical devices, safety alarms, and fitness equipment. Driven by the increasing scientific and technological interest and its huge commercial promise, wearable sensors will continue to evolve over the next few decades in providing a deeper understanding of the subjects' environment [91]. As the name suggests, the wearable sensors are packaged into wearable objects which can be directly worn on the body to help monitor health and/or provide clinically relevant data for care. Due to the burst in technological advancements (Figure 1.10), the recent focus has shifted to wearable sensing platforms, using stretchable and flexible electronics. However, these sensors are fabricated on bendable substrates which make microfabrication challenging, but opens up new avenues in research and applications.

Nowadays, various techniques such as transfer printing, screen printing, photolithography, microchannel molding, filling, and lamination are utilized in the realization of flexible sensors (Sections 3.4 and 3.7). Here, deformable or stretchable conducting electrodes are patterned onto a bendable/stretchable substrate [92]. However, these methods have some limitations such as high cost, multistep fabrication protocols, poor durability, and challenges in prototyping and

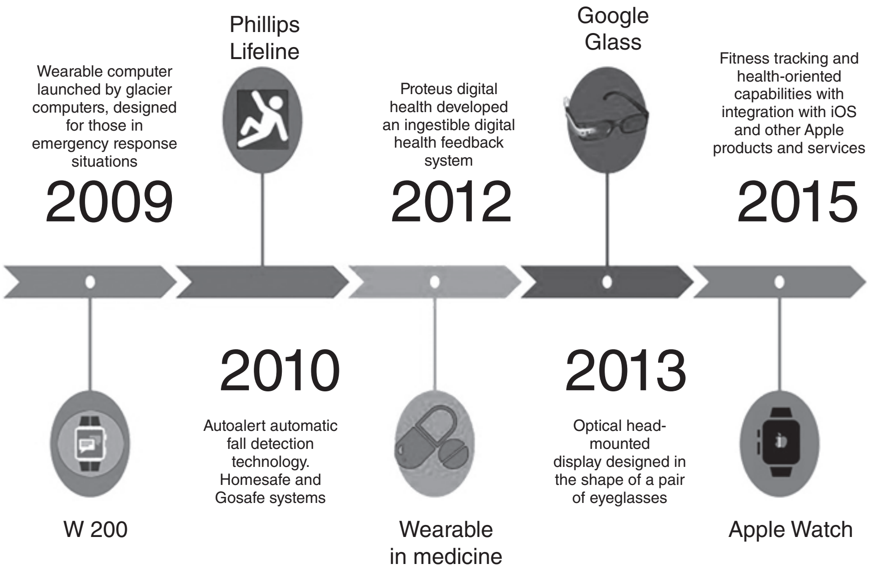


Figure 1.10 Timeline of wearable devices during the last decade.

scalability. The real challenge in wearable devices mainly lies in the acceptability of these technologies by the users/patients. For instance, monitoring of elderly people is one application that has been tentatively addressed since the beginning of the era of wearable monitoring, with the main motivation being the decrease in the costs of assistance for the chronic diseases typically affecting this category of patients. On the other hand, the limited familiarity of these patients with technology immediately highlighted the main limit of these systems. To turn this threat/challenge into an opportunity, several actions are needed.

1.2.4.3 Implantable Sensors

Implantable solid-state sensors play an important role especially in medical science not only to provide real-time treatment facilities to patients, but also in monitoring vital physiological statistics in humans. The ease of commercial manufacture, storage, and sensor performance in terms of accuracy and repeatability along with operations that are not dependent on user handling make the solid-state implantable solid-state sensors ideal for medical applications. Much before the burst of applications of implantable sensors in the medical industry in 1960s, they were developed in mid-1940s for space applications to monitor and broadcast real-time biological parameters of dogs and chimps [93]. With the advent of new materials and fabrication processes, the implantable sensors show promises for wider scope of application but are presently in their early stages of medical trials. In solid-state implantable sensors, the sensor element is invasive and communicates sensor data to an external system, worn either on the body or located remotely, for processing and display. In most implantable sensors, the active sensor element generates chemical signals or undergoes biological changes, which produces signals that have to be transformed into electrical signals for electronic detection. Even if piezoelectric sensors are used as detection systems, the electrical signal generated from the piezoelectric crystals must be modulated and amplified to a signal that can be exported from the body. Smart implantable sensors can collect data and store the information in buffers until the unit is interrogated by an external device.

Implantation of biomaterials and devices into soft tissues often causes foreign body response (FBR), which may interfere with the satisfactory working of the implanted device and/or lead to failure [94, 95]. The FBR involves overlapping acute and persistent inflammatory phases associated with collagenous coverage and proteins adsorption, which have no therapeutic remedies. The use of appropriate biomaterials for encapsulated packaging of implantable devices is an established way to protect devices from FBR. Such encapsulating materials include variety of synthetic polymers [96], such as PU, poly (2-methoxyethyl acrylate), and PVA [97], but found to have limited durability. Recently, polyester fabric coated with a biodegradable PGA sheet was developed and implanted in a rat model [98]. As the PGA degraded, cells deposited their extracellular matrix, much of which is collagen, on the polyester fabric. In terms of design, the implantable sensors must be capable of unobstructive and uninterferred data acquisition from the patient, be lightweight and small in size, its battery should last many years as it would be impractical to replace it frequently, not cause any kind of discomfort or damage to human tissues through overheating [99], and the sensor element need to be reliable and sensitive [100]. Present advancements in implantable sensors can be seen in sensor miniaturization and in the design of low-power circuitry [99].

Despite the recent developments in fabrication testing evaluation and statistical analysis of sensor performance, the acceptability and adoption of implantable sensors on the commercial scale are far from realization. This is because any failure of the devices could potentially lead to patient death or develop other forms of disease. Thus, to reform and revolutionize the field of implantable sensors, dedicated effort in engineering and technology coupled with public awareness of such devices need to be undertaken. Once the technology shows promises in comfort and effectiveness in real-time tracking of physiological parameters, there will be more patients willing to consent to monitoring, only to eliminate other painful and expensive methods of treatments [101].

1.3 Outline

There has been a rapid growth in the field of solid-state sensors in the last decade, mostly attributed to the fast advancements in monolithic fabrication processes, computer-controlled remote automation, and signal processing tools. The field of solid-state sensor technology has expanded its realm so much that it finds wide applications in industrial processes, healthcare systems, and household use. Its cost-effectiveness and portability has made it affordable, convenient, and user-friendly to the wide section of the global population and thus forms the highest trading market of this century. With the rise in integrated and automated remote sensing technology, sensor terminology, such as "sensor," "sensor element," and "sensor system," has been introduced and explained to facilitate coherent and consistent analysis of sensor technologies. The consistency and cost control in sensor system depend on advancements in fabrication procedures and tools. In this chapter, we discuss various fabrication procedures and tools including micromachining and lithography which lead to the advancements in the development of microsensor systems. Since modern solid-state sensors encompass much more than a transduction material, there are many opportunities for introducing novel materials in sensor systems which are discussed in subsequent chapters.

List of Abbreviations

AFM	Atomic Force Microscopy
AI	Artificial Intelligence
CAGR	Compound Annual Growth Rate
COVID-19	Coronavirus Disease 2019
ECG	Electrocardiogram
FPCB	Flexible Printed Circuit Boards
MEMS	Micro-electro-mechanical Systems
PCB	Printed Circuit Board
PWB	Printed Wiring Board
RFID	Radiofrequency Identification
SOC	System on Chip
STM	Scanning Tunneling Microscope
TEM	Transmission Electron Microscopy

References

1 Kafi, M.A., Paul, A., Vilouras, A., and Dahiya, R. (2020). Mesoporous chitosan based conformable and resorbable biostrip for dopamine detection. *Biosensors and Bioelectronics* 147: 111781.

2 Kim, J.Y., Park, J., Lee, M.J. et al. (2020). Diffusion-dependent graphite electrode for all-solid-state batteries with extremely high energy density. *ACS Energy Letters* 5 (9): 2995–3004.

3 Jeong, Y., Park, J., Lee, J. et al. (2020). Ultrathin, biocompatible, and flexible pressure sensor with a wide pressure range and its biomedical application. *ACS Sensors* 5 (2): 481–489.

4 Hosseini, E.S., Manjakkal, L., Shakthivel, D., and Dahiya, R. (2020). Glycine-chitosan-based flexible biodegradable piezoelectric pressure sensor. *ACS Applied Materials & Interfaces* 12 (8): 9008–9016.

5 Yogeswaran, N., Navaraj, W.T., Gupta, S. et al. (2018). Piezoelectric graphene field effect transistor pressure sensors for tactile sensing. *Applied Physics Letters* 113 (1): 014102.

6 Yan, C., Deng, W., Jin, L. et al. (2018). Epidermis-inspired ultrathin 3D cellular sensor array for self-powered biomedical monitoring. *ACS Applied Materials & Interfaces* 10 (48): 41070–41075.

7 Taube Navaraj, W., García Núñez, C., Shakthivel, D. et al. (2017). Nanowire FET based neural element for robotic tactile sensing skin. *Frontiers in Neuroscience* 11 (501): 40.

8 Lopez-Marzo, A.M. and Merkoci, A. (2016). Paper-based sensors and assays: a success of the engineering design and the convergence of knowledge areas. *Lab on a Chip* 16 (17): 3150–3176.

9 Nag, A., Mukhopadhyay, S.C., and Kosel, J. (2017). Wearable flexible sensors: a review. *IEEE Sensors Journal* 17 (13): 3949–3960.

10 Xu, Y., Hu, X., Kundu, S. et al. (2019). Silicon-based sensors for biomedical applications: a review. *Sensors* 19: 2908.

11 Luan, E., Shoman, H., Ratner, D.M. et al. (2018). Silicon photonic biosensors using label-free detection. *Sensors (Basel).* 18 (10): 3519.

12 PRNewswire (2020). *Global Automotive Sensor Market by Type (Temperature Sensors, Pressure Sensors, Motion Sensors, Speed Sensors, and Gas Sensors) and Application (Powertrain, Chassis, Body Electronics, Safety & Security, and Telematics): Global Opportunity Analysis and Industry Forecast, 2020–2027*. Portland: Allied Market Research.

13 McIntosh, J. (2008). *The Ancient Indus Valley: New Perspectives*. ABC-CLIO.

14 Lewis, M.J.T. (2001). *Surveying Instruments of Greece and Rome*. Cambridge University Press.

15 Northrup, C.C. (ed.) (2014). *Encyclopedia of World Trade: From Ancient Times to the Present*, vol. 4. Armonk, NY: Sharpe Reference.

16 Sleeswyk, A.W. and Sivin, N. (1983). Dragons and toads. The Chinese seismoscope OF A.D. 132. *Chinese Science* 6: 1–19.

17 H. Selin, "*Encyclopaedia of the History of Science, Technology, and Medicine in Non-western Cultures* Ed. 2," vol. 1, Berlin; New York Springer, 2008, pp. 197.

18 Lewis, O. (2017). Studies in ancient medicine, fragments and interpretation. In: *Praxagoras of Cos on Arteries, Pulse and Pneuma*, vol. 48, 350. Brill.

19 Hajar, R. (2018). The pulse from ancient to modern medicine: part 3. *Heart Views* 19: 117–120.

20 Lawrence, C. (1978). Physiological apparatus in the Wellcome Museum. 1. The Marey sphygmograph. *Medical History* 22 (2): 196–200.

21 Fung, Y.C. and Yih, C.-S. (1971). Biomechanics: a survey of the blood flow problem. In: *Advances in Applied Mechanics*, vol. 11, 65–130. Elsevier.

22 Mulcahy, R. (1997). *Medical Technology: Inventing the Instruments, Innovators Series*, 144. Oliver Press.

23 Reichert, P. (1978). A history of the development of cardiology as a medical specialty. *Clinical Cardiology* 1: 5–15.

24 Barold, S. (2003). Willem Einthoven and the birth of clinical electrocardiography a hundred years ago. *Cardiac Electrophysiology Review* 7 (1): 99–104.

25 Klooster, J.W. (2009). *Icons of Invention: The Makers of the Modern World from Gutenberg to Gates*, vol. 1. Greenwood Press: ABC-CLIO.

26 History.com Editors (2010). *First radio transmission sent across the Atlantic Ocean*. https://www.history.com/this-day-in-history/marconi-sends-first-atlantic-wireless-transmission (accessed 2 August 2023).

27 Fitzgerald, M. (2005). *Runner's World The Cutting-Edge Runner: How to Use the Latest Science and Technology to Run Longer, Stronger, and Faster*, 63. Rodale.

28 Tolmie, N. and Burich, M. (2005). *Textronics(TM) Introduces Heart Sensing Sports Bra; NuMetrex(TM) Sports Bra Monitors Heart Rate with Innovative Built-in Heart Monitor*. Wilmington: BusinessWire.

29 Islam, M.M., Rahaman, A., and Islam, M.R. (2020). Development of smart healthcare monitoring system in IoT environment. *SN Computer Science* 1 (3): 185.

30 Emerson, D.T. (1997). The work of Jagadis Chandra Bose: 100 years of millimeter-wave research. *IEEE Transactions on Microwave Theory and Techniques* 45 (12): 2267–2273.

31 Braun, A., Braun, E., and MacDonald, S. (1982). *Revolution in Miniature: The History and Impact of Semiconductor Electronics*. London: Cambridge University Press.

32 Graff, K.F. (1982). *A History of Ultrasonics, in Physical Acoustics*, vol. XV. New York: Academic Press.

33 Matté, J.A. (1996). *Forensic Psychophysiology Using the Polygraph: Scientific Truth Verification, Lie Detection*, vol. 1. Williamsville, New York: J.A.M. Publications.

34 Fleming, J.A. (1905). Instruments for converting alternating current into continuous current. *United States Patent Office*. United States Patent 803,684, U. F. Government, USA, 7 November 1905.

35 Bardeen, J. and Brattain, W. (1948). The transistor, a semi-conductor triode. *Physical Review B* 74: 230–231.

36 Bardeen, J. and Brattain, W. (1950). Three-electrode circuit element utilizing semiconductor materials. U. S. Patent 2,524,035.

37 Kilby, J. (1964). Miniaturized electronic circuits. US Patents, U. S. P. Office, Texas Instruments.

38 Noyce, R.N. (1959). Semiconductor device-and-lead structure. US2981877A, U. P. Office, Fairchild Semiconductor Corp.

39 Bellis, M. (2020). *The History of the Integrated Circuit (Microchip)*. ThoughtCo. thoughtco.com/history-of-integrated-circuit-aka-microchip-1992006.

40 Kilby, J., Merryman, J., and Van, T.J. (1972). Miniature electronic calculator. Google Patents, US3819921A, U. S. P. Office, Texas Instruments Inc.

41 Instrument Society of America (1975). *Electrical Transducer Nomenclature and Terminology. ANSI Standard MC6.1*. Research Triangle Park, North Carolina: Instrument Society of America.

42 Drude, P. (1889). Ueber Oberflächenschichten. *Annalen der Physik* 272 (2): 532–560.

43 Grzegorz, G., Ivan, P., Greene, J.E., and Lars, H. (2019). Paradigm shift in thin-film growth by magnetron sputtering: From gas-ion to metal-ion irradiation of the growing film. *Journal of Vacuum Science & Technology A* 37 (6): 060801.

44 Burnside, S.D., Shklover, V., Barbe, C. et al. (1998). Self-organization of TiO2 nanoparticles in thin films. *Chemistry of Materials* 10 (9): 2419–2425.

45 Luo, H., Cardinal, C.M., Scriven, L.E., and Francis, L.F. (2008). Ceramic Nanoparticle/Monodisperse Latex Coatings. *Langmuir* 24 (10): 5552–5561.

46 Nagao, D., Goto, K., Ishii, H., and Konno, M. (2011). Preparation of asymmetrically nanoparticle-supported, monodisperse composite dumbbells by protruding a smooth polymer bulge from rugged spheres. *Langmuir* 27 (21): 13302–13307.

47 Xu, J., Wong, D.H.C., Byrne, J.D. et al. (2013). Future of the particle replication in nonwetting templates (PRINT) technology. *Angewandte Chemie International Edition* 52 (26): 6580–6589.

48 Koide, Y., Such, M.W., Basu, R. et al. (2003). Hot microcontact printing for patterning ITO surfaces. methodology, morphology, microstructure, and OLED charge injection barrier imaging. *Langmuir* 19 (1): 86–93.

49 Resnick, D.J., Sreenivasan, S.V., and Willson, C.G. (2005). Step & flash imprint lithography. *Materials Today* 8 (2): 34–42.

50 Acharya, G., Shin, C.S., McDermott, M. et al. (2010). The hydrogel template method for fabrication of homogeneous nano/microparticles. *Journal of Controlled Release* 141 (3): 314–319.

51 Hou, S., Yang, K., Qin, M. et al. (2008). Patterning of cells on functionalized poly(dimethylsiloxane) surface prepared by hydrophobin and collagen modification. *Biosensors and Bioelectronics* 24 (4): 912–916.

52 Fernandes, T.G., Diogo, M.M., Cabral, J.M.S. et al. (2013). Microscale technologies for stem cell culture. In: *Stem Cell Bioprocessing*, 143–175. Woodhead Publishing.

53 Otsuka, H., Ohshima, H., and Makino, K. (2014). Chapter 11 – Micropatterning of cell aggregate in three dimension for in vivo mimicking cell culture. In: *Colloid and Interface Science in Pharmaceutical Research and Development* (ed. H. Ohshima and K. Makino), 223–241. Amsterdam: Elsevier.

54 Tan, W. and Desai, T.A. (2003). Microfluidic patterning of cells in extracellular matrix biopolymers: effects of channel size, cell type, and matrix composition on pattern integrity. *Tissue Engineering* 9 (2): 255–267.

55 Suri, S., Singh, A., Nguyen, A.H. et al. (2013). Microfluidic-based patterning of embryonic stem cells for in vitro development studies. *Lab on a Chip* 13 (23): 4617–4624.

56 Berthier, E., Warrick, J., Casavant, B., and Beebe, D.J. (2011). Pipette-friendly laminar flow patterning for cell-based assays. *Lab on a Chip* 11 (12): 2060–2065.

57 Kelly, A., Ballerini, L., Lowery, M. et al. (2017). Engineering the neural interface. In: *Comprehensive Biomaterials II* (ed. P. Ducheyne), 642–660. Oxford: Elsevier.

58 Kong, J., Franklin, N.R., Zhou, C. et al. (2000). Nanotube molecular wires as chemical sensors. *Science* 287 (5453): 622–625.

59 Harris, K.D., Huizinga, A., and Brett, M.J. (2002). High-speed porous thin film humidity sensors. *Electrochemical and Solid-State Letters* 5 (11): H27–H29.

60 Besteman, K., Lee, J.-O., Wiertz, F.G.M. et al. (2003). Enzyme-coated carbon nanotubes as single-molecule biosensors. *Nano Letters* 3 (6): 727–730.

61 Ito, Y. and Fukusaki, E. (2004). DNA as a ‘nanomaterial’. *Journal of Molecular Catalysis B: Enzymatic* 28 (4–6): 155–166.

62 Penza, M., Antolini, F., and Antisari, M.V. (2004). Carbon nanotubes as SAW chemical sensors materials. *Sensors and Actuators B: Chemical* 100 (1–2): 47–59.

63 Mahar, B., Laslau, C., Yip, R., and Sun, Y. (2007). Development of carbon nanotube-based sensors – a review. *IEEE Sensors Journal* 7 (2): 266–284.

64 Kokarneswaran, M., Selvaraj, P., Ashokan, T. et al. Discovery of carbon nanotubes in sixth century BC potteries from Keeladi, India. *Scientific Reports* 10: 19786.

65 Newton, M.D. and Stanton, R.E. (1986). Stability of buckminsterfullerene and related carbon clusters. *Journal of the American Chemical Society* 108 (9): 2469–2470.

66 Iijima, S. (1991). Helical micro-tubules of graphitic carbon. *Nature* 345: 56–58.

67 Tracy, M. (2019). The legendary life of Paul Eisler, the father of pcb circuit boards. In: *Oneseine Enterprise Building A*. Shajing, Baoan, Shenzhen, China: Shixiaganglian Industrial Park.

68 Paul, E. (1944). Manufacture of electric circuit components. US Patent Office, in *Google Patents*, US2441960A. USA: Eisler Paul.

69 Paul, E. (1949). Electric capacitor and method of making it. US Patent Office, *Google Patents*, US2607825A. USA: Eisler Paul.

70 Kraemer, D., Poudel, B., Feng, H.-P. et al. (2011). High-performance flat-panel solar thermoelectric generators with high thermal concentration. *Nature Materials* 10 (7): 532–538.

71 Mok, J.W., Hu, Z., Sun, C. et al. (2018). Network-stabilized bulk heterojunction organic photovoltaics. *Chemistry of Materials* 30 (22): 8314–8321.

72 Zhang, L., Ji, H., Huang, H. et al. (2020). Wearable circuits sintered at room temperature directly on the skin surface for health monitoring. *ACS Applied Materials & Interfaces* 12 (40): 45504–45515.

73 Laghrib, F., Saqrane, S., El Bouabi, Y. et al. (2021). Current progress on COVID-19 related to biosensing technologies: new opportunity for detection and monitoring of viruses. *Microchemical Journal* 160: 105606.

74 Singh, V.K., Chandna, H., Kumar, A. et al. (2020). IoT-Q-band: a low cost internet of things based wearable band to detect and track absconding COVID-19 quarantine subjects. *Transactions on Internet of Things* 6 (21): 4.

75 Xue, X., Ball, J.K., Alexander, C., and Alexander, M.R. (2020). All surfaces are not equal in contact transmission of SARS-CoV-2. *Matter* 3 (5): 1433–1441.

76 Tsumura, A., Koezuka, H., and Ando, T. (1986). Macromolecular electronic device: field-effect transistor with a polythiophene thin film. *Applied Physics Letters* 49 (18): 1210–1212.

77 Tang, C.W. and VanSlyke, S.A. (1987). Organic electroluminescent diodes. *Applied Physics Letters* 51 (12): 913–915.

78 Tsumura, A., Fuchigami, H., and Koezuka, H. (1991). Field-effect transistor with a conducting polymer film. *Synthetic Metals* 41 (3): 1181–1184.

79 Dyer-Smith, C., Nelson, J., Li, Y., and Kalogirou, S.A. (2018). Chapter I-5-B – organic solar cells. In: *McEvoy's Handbook of Photovoltaics*, 3e, 567–597. Academic Press.

80 Jager, E.W.H. and Inganas, O. (2016). Electrochemomechanical devices from conjugated polymers. In: *Reference Module in Materials Science and Materials Engineering* (ed. S. Hashmi). Elsevier.

81 Peng, H., Sun, X., Weng, W. et al. (2017). 2 – Synthesis and design of conjugated polymers for organic electronics. In: *Polymer Materials for Energy and Electronic Applications*, 9–61. Academic Press.

82 Wang, Y.J. and Yu, G. (2019). Conjugated polymers: from synthesis, transport properties, to device applications. *Journal of Polymer Science Part B: Polymer Physics* 57 (23): 1557–1558.

83 Paul, A. and Bhattacharya, B. (2010). DNA functionalized carbon nanotubes for nonbiological applications. *Materials and Manufacturing Processes* 25 (9): 891–908.

84 MacFarlane, L.R., Shaikh, H., Garcia-Hernandez, J.D. et al. (2020). Functional nanoparticles through TT-conjugated polymer self-assembly. *Nature Reviews Materials* 6: 7–26.

85 Zeglio, E., Rutz, A.L., Winkler, T.E. et al. (2019). Conjugated polymers for assessing and controlling biological functions. *Advanced Materials* 31 (22): 1806712.

86 Che, B., Zhou, D., Li, H. et al. (2019). A highly bendable transparent electrode for organic electrochromic devices. *Organic Electronics* 66: 86–93.

87 Pankow, R.M. and Thompson, B.C. (2020). The development of conjugated polymers as the cornerstone of organic electronics. *Polymer* 207: 122874.

88 Kafi, M., Paul, A., Vilouras, A., and Dahiya, R. (2018). Chitosan-Graphene Oxide based ultra-thin conformable sensing patch for cell-health monitoring. *Presented at IEEE Sensors* (28–31 October 2018). New Delhi: IEEE.

89 Lima, C.G.A., de Oliveira, R.S., Figueiró, S.D. et al. (2006). DC conductivity and dielectric permittivity of collagen–chitosan films. *Materials Chemistry and Physics* 99 (22): 284–288.

90 Vilouras, A., Paul, A., Kafi, M.A., and Dahiya, R. (2018). Graphene oxide-chitosan based ultra-flexible electrochemical sensor for detection of serotonin. *Presented at 2018 IEEE Sensors* (28–31 October 2018).

91 An, B.W., Gwak, E.-J., Kim, K. et al. (2016). Stretchable, transparent electrodes as wearable heaters using nanotrough networks of metallic glasses with superior mechanical properties and thermal stability. *Nano Letters* 16 (1): 471–478.

92 Hu, W., Niu, X., Li, L. et al. (2012). Intrinsically stretchable transparent electrodes based on silver-nanowire-crosslinked-polyacrylate composites. *Nanotechnology* 23 (34): 344002.

93 Martin, S., Duncan, E., Inmann, A., and Hodgins, D. (2013). 8 – Sterilisation considerations for implantable sensor systems. In: *Implantable Sensor Systems for Medical Applications*, 253–278. Woodhead Publishing.

94 Malik, A.F., Hoque, R., Ouyang, X. et al. (2011). Inflammasome components Asc and caspase-1 mediate biomaterial-induced inflammation and foreign body response. *Proceedings of the National Academy of Sciences* 108 (50): 20095.

95 Goswami, R., Arya, R.K., Biswas, D. et al. (2019). Transient receptor potential vanilloid 4 Is required for foreign body response and giant cell formation. *The American Journal of Pathology* 189 (8): 1505–1512.

96 Li, R., Wang, L., Kong, D., and Yin, L. (2018). Recent progress on biodegradable materials and transient electronics. *Bioactive Materials* 3 (3): 322–333.

97 Mulinti, P., Brooks, J.E., Lervick, B. et al. (2018). 10 – Strategies to improve the hemocompatibility of biodegradable biomaterials. In: *Hemocompatibility of Biomaterials for Clinical Applications*, 253–278. Woodhead Publishing.

98 Yekrang, J., Semnani, D., Zadbagher, A. et al. (2017). A novel biodegradable micro-nano tubular knitted structure of PGA braided yarns and PCL nanofibres applicable as esophagus prosthesis. *Indian Journal of Fibre & Textile Research* 42: 264–270.

99 Islam, S.U., Ahmed, G., Shahid, M. et al. (2017). Chapter 2 – Implanted wireless body area networks: energy management, specific absorption rate and safety aspects. In: *Ambient Assisted Living and Enhanced Living Environments* (ed. C. Dobre, C. Mavromoustakis, N. Garcia, et al.), 17–36. Butterworth-Heinemann.

100 Alam, M.M. and Ben Hamida, E. (2014). Surveying wearable human assistive technology for life and safety critical applications: standards, challenges and opportunities. *Sensors (Basel, Switzerland)* 14 (5): 9153–9209.

101 Eltorai, A.E.M., Fox, H., McGurrin, E., and Guang, S. (2016). Microchips in medicine: current and future applications. *BioMed Research International* 2016: 1743472–1743472.