1 Introduction

1.1 Wireless Sensing Platforms

Energy harvesting technologies have spurred interest in the academic and industrial communities due to the emerging applications of miniature, low-power, wireless sensors. Concepts such as the Internet of Things (IoT) envision myriad networked devices used to integrate and automate homes, offices, factories – in other words, everything [1, 2]. One of the challenges for such devices is their ability to operate for long periods of time autonomously, i.e., without the need to be connected to a wired power supply or to substitute or recharge their batteries.

A notable milestone toward miniature wireless sensor nodes has been the smart dust project by University of California, Berkeley, researchers in the late 1990s [3]. The smart dust project introduced the concept of autonomous sensing and communication cubic-millimeter-sized motes (i.e., small particles) forming a massive distributed sensor network [3]. As a result, several wireless sensing platforms have been developed in an attempt to implement the smart dust concept. Widely popular implementations of such sensing platforms, albeit without achieving the ultimate cubic millimeter volume vision, have been the Mica mote [4] and subsequently the Telos mote [5] integrating a low-power microcontroller, sensor interface circuitry and a radio transceiver.

An alternative technology toward implementing ultralow-power wireless sensing platforms has been radio frequency identification (RFID) technology based on radar principles and backscatter communication [6]. In such systems, passive sensing and identification tags comprise ultralow-power radio transceivers that operate based on antenna load modulation that does not require an amplifier because the necessary power for both powering the tag and for communication is provided by an interrogator reader device [6].

Finally, the increased interest for ultralow-power, energy autonomous, wireless sensing platforms has been further fueled by the fifth generation (5G) communication systems that attempt to implement a massive number of interconnected devices communicating at low bit rates [7]. As the number of interconnected devices and potential for new applications keeps increasing, it is only natural to expect that the interest for energy autonomous, wireless sensing platforms will continue into the sixth generation (6G) systems and beyond.

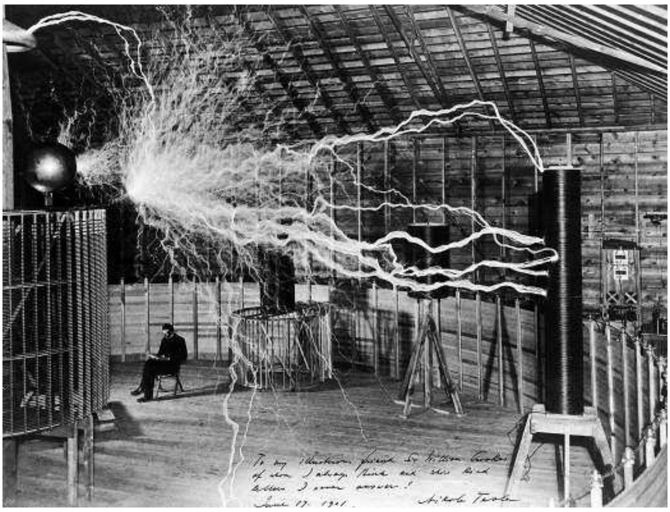

Figure 1.1 Nikola Tesla, with his equipment for producing high-frequency alternating currents. Credit: Wellcome Collection. Attribution 4.0 International (CC BY 4.0)

1.2 Energy Harvesting Revolution

The physics behind the commonly employed energy harvesting technologies, solar, mechanical, thermal, and radio frequency, has been known for many years. For example, more than 100 years ago, Tesla envisioned the wireless transmission of power. Figure 1.1 shows a celebrated photo of Tesla in his laboratory in Colorado Springs. In another example, more than 100 years ago, Gulielmo Marconi began his experiments in wireless telegraphy in Vila Griffone, Bologna, Italy. The photo shown in Figure 1.2 is a setup of his laboratory in the Marconi Museum, where one can see on his desk a disc-shaped device that was a thermocouple, a thermoelectric generator that he used in his experiments.

One could probably come up with numerous other examples. Advances in materials and fabrication techniques have enabled the miniaturization and the performance improvement of such energy harvesting devices that make them suitable for low-power wireless sensors. Combined with advances in electronic design and integrated circuit technologies that have led to the reduction of operating power of electronic circuits, the vision of energy harvesting powered wireless sensor platforms becomes more and more possible.

1.3 This Book

The topic of energy harvesting technologies is very broad and diverse, given that each of the energy harvesting technologies represents a completely different field

Figure 1.2 Marconi's laboratoy at Villa Griffone, Bologna, Italy.

of research. This book discusses the main energy harvesting technologies, namely solar, kinetic, thermal, and electromagnetic (EM), together with an introduction to power converters and energy storage. We try to provide an answer to questions such as how much power can be harvested and what are the main challenges in implementing these harvesting systems.

Table 1.1 presents indicative performance results from different types of energy harvesters with emphasis on low-profile transducers suitable for micropower generation. There exists a large variation among the size of the transducers and the amount of energy that can be generated. As a result, the final selection of the employed type of transducer depends greatly on the application requirements and scenario, which makes the presented results of Table 1.1 only indicative of the potential of the various harvesting methods.

Table 1.1 Indicative harvested power values from different transducer types [8].

Energy source	Harvested power	Conditions / available power
Light / solar	60 mW	6.3 cm × 3.8 cm flexible a-Si solar cell AM1.5 Sunlight (100 mW/cm^2) [9]
Kinetic	8.4 mW	Shoe-mounted piezoelectric [10]
Thermal	0.52 mW	Thermoelectric generator (TEG), $\Delta T = 5.6$ K [11]
Electromagnetic	1.5 μW	Ambient power density 0.15 μW/cm^2 [12]

Each transducer technology has distinct advantages and disadvantages. For example, solar energy is ubiquitous, whereas solar harvesting is challenging in indoor scenarios and during night or cloudy conditions. Thermal energy harvesters are typically hampered by a low transducer efficiency, especially when a low-temperature gradient is present, while kinetic energy harvesters are sensitive to the natural vibration frequencies of the harvester and application settings.

When it comes to ambient EM energy harvesting, the available energy density is usually orders of magnitude below the corresponding values of the other energy sources, although measurement campaigns in crowded urban settings have shown the possibility of harvesting a useful amount of EM energy from the ambient [13, 14, 15], especially using wideband or multiband harvesters. Nonetheless, EM energy harvesters are intimately related to systems exploring intentional EM radiation to power up electronic devices, wireless power transfer, with RFID technology being a notable application example that already enjoys commercial success.

The dc voltage output of the various energy harvesting transducers can vary significantly from the value that is necessary to operate the microcontroller, the transceiver, and sensor circuits of the wireless sensing platform. Consequently, it is necessary to use a dc-dc converter circuit in order to bring the voltage to a desired value and furthermore, regulating circuitry maybe necessary in order to minimize the variation of voltage. All these circuits penalize further the overall power conversion efficiency of the energy harvesting system and must be carefully selected and designed.

Finally, due to the time varying and many times random nature of the available ambient energy, the implementation of energy autonomous circuits for communication and sensing dictates the integration of multiple energy harvesters in order to ensure an average energy supply. In this case, combining the dc outputs of each energy harvesting device must also be done carefully because the efficiency of energy harvesting devices is also dependent on the load that is connected to them and the interconnection of different harvesters that present different and variable loads to each other will also affect efficiency.

These considerations demonstrate on one hand the great challenge for the designer in order to design an energy harvesting assisted wireless sensing platform, but on the other hand, they show the broad nature and the large amount of possibilities that arise by exploring the different disciplines related to the field of energy harvesting.

2 2D-3D Integration for Autonomous Sensors

Sangkil Kim[1]
Pusan National University, South Korea

2.1 Introduction

The advances in energy harvesting technologies for powering low-power sensing platforms are intimately related with low-cost fabrication methods that are compatible with low-cost, flexible substrate materials. Additive manufacturing techniques provide such a platform to fabricate sensors and electronics with low cost, implicitly generate less waste, utilize flexible and low-cost substrates such as paper and plastics, and moreover enable a very quick turnaround, on-demand fabrication and design iteration that facilitates both research and in a way revolutionizes production [16]. In this chapter, we focus on inkjet printing fabrication, an additive manufacturing technique that has shown great potential in the last decade in flexible electronics on both plastics and organic paper substrates, fabricating radio frequency electronic circuits using low-cost [17] and medium-cost equipment [16] even up to millimeter waves. Inkjet printing is suitable for fabricating solar cells, thermoelectric generators, microelectromechanical systems (MEMS) transducers, circuit components such as inductors and capacitors, and transmission lines and antennas with sufficient resolution and provides a platform for packaging and integrating, integrated circuits (ICs), sensors, and interconnects [16]. The recent advances in other additive manufacturing technologies such as 3D printing will undoubtedly help further develop this exciting field of energy harvesting assisted wireless sensor platforms.

The demands for flexible sensors keep increasing as the market rapidly grows for ubiquitous computing, logistics, wearable/implantable electronics, and the Internet of Things (IoT). Flexible sensors have many advantages, such as flexibility, and functionality. They also allow low-cost implementation over some conventional sensors when they are integrated with nanotechnology-based novel materials and cost-efficient fabrication methods such as inkjet printing technology. The flexible sensors can be mounted on rugged/curved surfaces with low cost, which allow them large-scale deployment. The lifetime of the sensor is also an important factor for stable sensing. The energy harvesting and storing technology for flexible sensors is necessary to implement standalone autonomous sensor systems. Selecting proper flexible materials such as paper, liquid crystal polymer (LCP), and polyimide for the substrate material depending on the

[1] Edited by Apostolos Georgiadis.

application is an important step in the implementation of flexible electronics. However, it is more important to choose and understand properly the materials used for sensing functions, electronics, and energy sources as well as fabrication methods that are compatible with a desired flexible sensor application.

Inkjet printing technology is widely utilized and studied as a novel fabrication method compared to the conventional fabrication methods such as milling and wet etching. Numerous electronics utilizing inkjet printing technology such as the Internet of Things (IoT), radio frequency identification tags (RFIDs), and wireless sensor networks (WSNs) have been demonstrated [18, 19, 20]. It is an additive fabrication method that deposits the controlled amount of functionalized ink such as silver nanoparticles, polymers, and nanocarbon structures on a desired position. This technology is cost efficient and environmentally friendly because it doesn't produce any byproducts due to its additive fabrication property. Small feature sizes (less than 50 μm) and arbitrary geometries can be also easily achieved without any masking [21, 22, 23]. Inkjet printing technology has great advantages for implementation of flexible sensors because it is able to print various nanoparticle-based materials, including metals, polymers, and sensing materials. Furthermore, inkjet printing technology can print materials on very thin flexible substrate without damaging the substrate.

Inkjet printing technology has attracted significant interest from many researchers due to the development of numerous types of nanoparticle-based inks such as metals, polymers, and carbon-based materials [24, 25, 26]. The silver nanoparticle inks allow metallization of electronic components and devices using inkjet printing technology, and the development of polymer inks enables printing numerous electronic components like such as transistors, inductors, and capacitors [27, 28]. Also, inkjet printing of nanocarbon materials such as carbon nanotube (CNT) and graphene significantly improved the sensitivity, selectivity, and application spectrum of inkjet-printed flexible sensors [29, 30].

Toward standalone autonomous flexible sensor platforms, energy harvesting is one of the most important design specifications because the available energy affects the system-level design of the sensor platform. There are many types of power sources such as batteries, solar cells, and nanogenerators. The solar cells and batteries can support relatively high power, but they need large area and are not suitable for flexible electronic applications. However, nanowire-based nanogeneratrors [31], for example, are becoming a promising power source for the flexible sensors because they can convert bending motions to power by utilizing, for example, piezoelectric effects. The generated power from the nanogenerator can be stored in printed flexible capacitors, which can be used to operate the sensor platform.

In this chapter, novel materials and fabrication technology for flexible sensors are introduced. The characteristics of nanomaterials including silver nanoparticles, printable polymers, and carbon-based materials such as CNT and graphene are presented, and inkjet printing technology is discussed as a novel fabrication method for flexible sensor system. The state-of-the-art nano-technologies

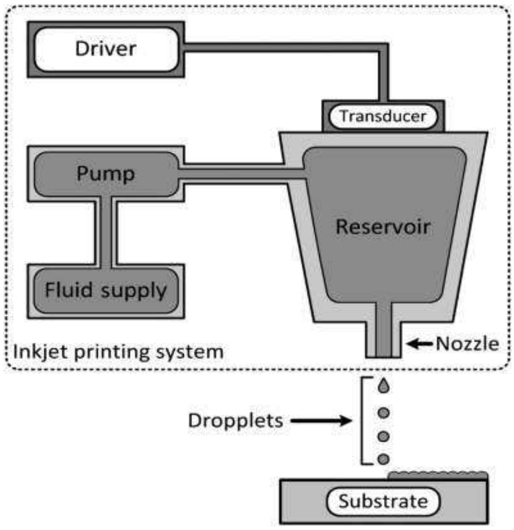

Figure 2.1 Inkjet printing system.

for energy harvesting such as nanowire-based nanogenerators and printed flexible capacitors are also introduced.

2.2 Inkjet Printing Technology

Inkjet printing enables the implementation of printed electronics on various flexible and organic substrates. Inkjet printing is able to print numerous materials such as metals, carbon-based nanostructures, and polymers [24, 25, 26]. It is a cost-efficient, environmentally friendly, and fast fabrication method due to its additive fabrication properties.

2.2.1 Types of Inkjet Printing

The concept of inkjet printing is relatively simple, and it is presented graphically in Figure 2.1. A liquid ink in a reservoir is jetted on a substrate through a nozzle. A desired pattern can be printed by moving the nozzle or substrate to deposit the ink drops on the correct positions.

There are two main inkjet printing methods: the continuous inkjet (CIJ) method and the drop-on-demand (DOD) method, which are shown in Figure 2.2a and 2.2b respectively. CIJ ejects ink drops continuously from the reservoir at a constant frequency (50 kHz–170 kHz), as shown in Figure 2.2c. The ejected drops are charged by charging plates, and the charged drops are directed by a pair of electrodes to print on a substrate or to a gutter for reuse. The advantages of the CIJ method are the high velocity of the ejected ink drops and the high drop ejection frequency. The high velocity of the ink droplets allows

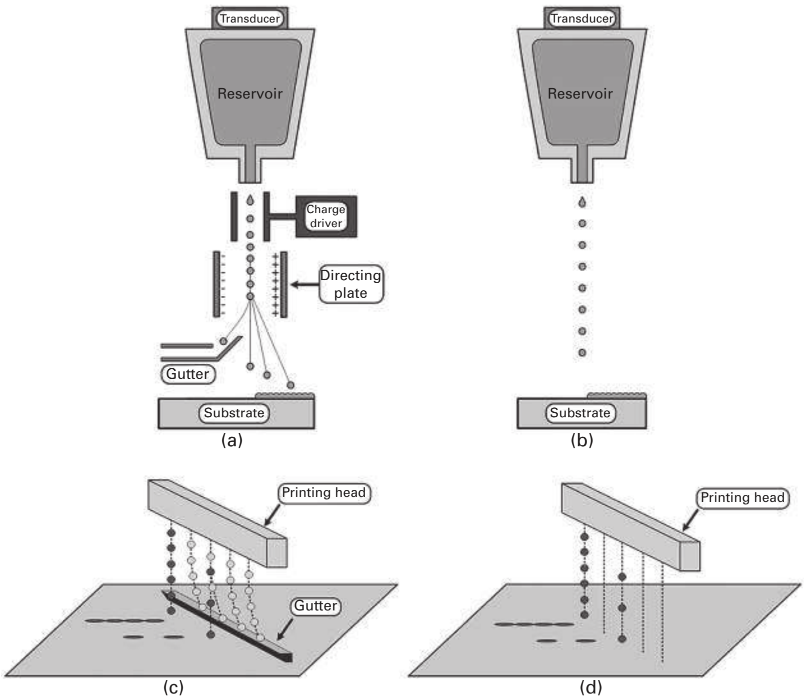

Figure 2.2 Continuous and DOD inkjet printing.

for a relatively long distance between a substrate, and a printing head and the high ejection frequency allows for high-speed printing. The continuous ejection of the ink mitigates the clogging of the printing nozzles. Therefore, volatile solvents such as alcohols can be printed easily. However, the CIJ system requires inks that can be electrostatically charged, and continuous viscosity monitoring is necessary.

DOD printing is similar to CIJ in that a transducer generates a pressure in order to eject a drop of ink. However, the ejected drops are not directed by electrostatic plates. A signal is sent to the transducer, and the transducer ejects the ink drop when it is needed, as shown in Figure 2.2d. DOD printing can use a wider range of inks with varying viscosities and surface tensions, and a higher printing resolution can be achieved compared to the CIJ method. However, clogging of the nozzles happens easily due to the ink drying and the inconsistent use of the nozzles.

There are several types of actuators such as piezoelectric, thermoelectric, and electrodynamic, which generate a pulse in the reservoir in order to eject the ink drop as shown in Figure 2.3. The piezoelectric and the thermoelectric actuators generate the pressure pulse in the reservoir while the electrodynamic actuator creates an ink drop by disturbing the surface tension of the meniscus formed at the end of the nozzle. The thermoelectric actuator generates heat

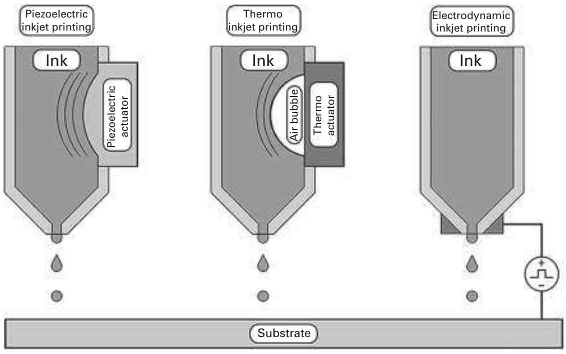

Figure 2.3 Actuator types of the inkjet printing technology.

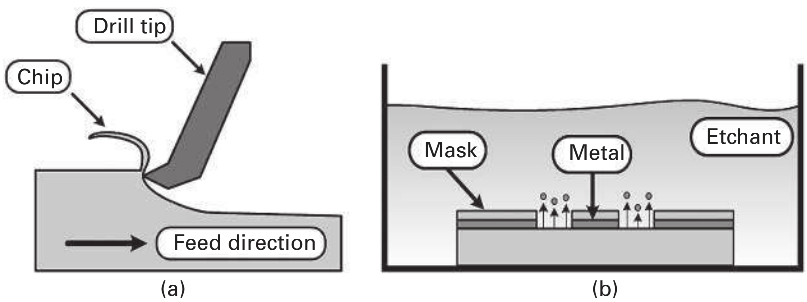

Figure 2.4 Subtractive fabrication methods: (a) milling and (b) wet etching.

causing vaporization of the ink in the reservoir to form a bubble, which ejects a droplet through a nozzle. Small drop sizes and high nozzle density are the advantages of a thermo actuator, but it has limitations on usable ink types. The inks should be able to be vaporized as well as to withstand high temperature. The electrodynamic actuator is able to create an ink drop of a very small size but has disadvantages such as low nozzle density, system complexity, and slow printing speed. The piezoelectric actuator utilizes a piezoelectric material in the reservoir to generate a pressure pulse to eject an ink drop. This type of inkjet printing technology is widely used in the research area because the piezoelectric actuator is compatible with a wider variety of inks.

2.2.2 Inkjet Printing Technology as a Fabrication Method

Inkjet printing technology is an additive method unlike a subtractive method including the wet etching and milling techniques. The wet etching and the milling techniques are widely used fabrication methods due to advantages such as rapid prototyping at low cost. The milling technique cuts and the wet etching technique washes away the unwanted materials selectively, utilizing a milling machine or an etchant as shown in Figure 2.4.

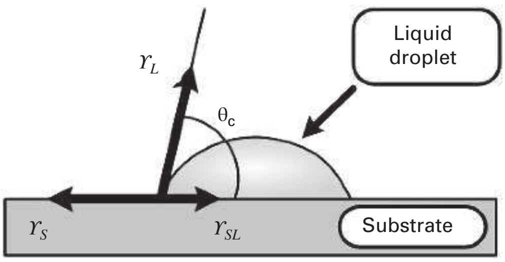

Figure 2.5 Surface energy.

The milling technique requires a milling machine, substrate, and cutting bits that have a size equal to or smaller than the smallest feature size of the desired pattern. A variety of features such as holes and slots can be created by the milling process, and this process is compatible with lots of materials, including metals and ceramics with tolerance down to 25 μm. However, a lot of byproducts are formed like chips and rough edges because of the cutting of the drill bit (Figure 2.4a). This method is suitable to process hard and relatively thick materials, but can be hardly used on thin flexible substrates as the bit removes part of the substrate. The wet etching technique is also commonly used to fabricate a printed circuit boards (PCBs). The etchants are solvent containing highly corrosive acids that dissolve a metal or a substrate (Figure 2.4b). The used etchants combined with the discarded materials form waste produced by the fabrication process, and they require special treatment for safety and environmental protection reasons.

Inkjet printing technology is a more efficient and environmentally friendly fabrication method compared to those conventional fabrication methods. It drops ink on an exact desired position. Therefore, there are no wasted materials because the inkjet printing produces no byproducts such as the acid etchant. In addition, a reasonably high resolution down to 50 μm can be achieved with high repeatability and without any special surface treatment such as masking. It is possible to improve the printing resolution to submicrometer values [23]. Furthermore, inkjet printing is compatible with very thin or flexible substrate because it doesn't damage the substrate surface.

2.2.3 Inkjet Printing and Surface Energy

Each substrate has different physical surface properties such as roughness and surface energy that result in different inkjet printability [22, 32]. The surface energy of the substrate is a very important factor because it determines substrate wetting. The difference in surface free energy between the printed ink drop and the substrate determines whether the ink wets the substrate surface (spread on the substrate) or not (forms a ball on the surface). It can be defined by the contact angle θ_c as shown in Figure 2.5.